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FVS - Fire Model:
Model Description

Working Document

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U.S.D.A. Forest Service
Intermountain Research Station

by

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1.0 Introduction

1.1 Project Rationale

Fire is an integral part of forest ecosystem function and management. The Forest Vegetation Simulator (FVS) is a family of forest vegetation simulation models based on the Prognosis Model (Stage 1973, Crookston 1990, Moeur 1985, Wykoff 1986, Crookston and Stage 1991, Ferguson and Crookston 1991). FVS is used widely by forest managers to predict future forest conditions as affected by various vegetation management actions. Up to now, fire as an ecosystem component has not been explicitly represented in this modeling system. Yet, several models have been developed to represent fuel dynamics (Keane *et al.* 1989) (with and without fire), the fire itself (Albini 1976, Rothermel 1972), and the effects of fire (Keane *et al.* 1989). These models can be used to predict how fuel management treatments influence fire behavior and effects on vegetation.

There is a need to link FVS with fire models. The fuel and fire models can benefit from FVS by using FVS-generated predictions of tree growth, mortality, and regeneration establishment as they are influenced by simulated management practices. The FVS can benefit from the fuel and fire models by being able to directly represent the effects of fire on competition and site preparation. The fuel model, by itself, would be worthwhile linking to FVS because it provides predictions on the dynamics of dead tree decomposition of interest to wildlife biologists.

In addition, there are many extensions to the base vegetation portion of FVS that represent insect and disease dynamics. There are known interactions between these ecosystem components and fire that could be represented given a fire model is linked to the complete system. Lastly, there are a set of computer programs that use FVS outputs to predict variables directly related to wildlife management. The outputs from these computer programs would reflect fire effects if fire is represented in the FVS.

1.2 Project Objectives

Project scientists at the Intermountain Research Station Fire Sciences Laboratory in Missoula, Montana have created fuel, fire behavior, and fire effects models. Scientists at the Intermountain Research Station Forestry Sciences Laboratory in Moscow, Idaho are primary authors of the Prognosis Model and have cooperated in building most of the insect and disease extensions.

1.2.1 Primary Project Objective

The **primary** objective of this project was to integrate the existing fire model components into the FVS system. Scientists at both the Missoula fire laboratory and the Moscow forest science laboratory have collaborated on accomplishing this objective. A team of modelers from ESSA Technologies was contracted to implement and test model code.

There are two forms of FVS, a single stand form (herein called Standard FVS) useful for projecting one stand forward in time without representing the dynamic interactions between stands, and a multi-

stand form (PPE, Parallel Processing Extension; Crookston and Stage 1991) useful for projecting many stands (a landscape) forward in time with the dynamic interactions between stands being explicitly represented. The fire components are currently incorporated into the PPE and will later be incorporated into standard FVS.

1.2.2 Secondary Project Objectives

The linkages to the Standard FVS will be done using methods currently used to link other independent model extensions. The word independent means, in this context, that the fire components will dynamically interact with the primary vegetation components but not with the pest components, such as the root disease submodel, unless changes are made in those models to include such interactions. Those changes are beyond the scope of this project.

Initially, the linkages to the PPE will be done independent of the Westwide Pine Beetle Model (PBM) (Beukema *et al.* 1994). At a later date, however, the fire model will be linked to the PBM. The PBM includes a provisional fuels and fire effects model that will be replaced with the fuels and fire effects model describe here. Therefore, the fire model will interact with the PBM, as discussed below. This approach will help ensure that the new fire model will be used by future insect and disease models that operate on a landscape scale and are based on the techniques used in the PBM.

There is a great deal of interest in reporting the state of dead woody materials in a form useful to wildlife and pest managers. Additional detail in the status of standing dead material is needed by the non-fuel managers. A final secondary objective of this work is to build the fuel components of the model so that they are adequate for the needs of other model components and managers that need information on dead woody (standing and down) material.

1.3 Activities to Date

December 6-9, 1993 the following people meet in Moscow to begin FVS-Fire modeling work:

James K. Brown, Project Leader, Fire Effects (RWU 4403)
Elizabeth D. Reinhardt, Research Forester, Fire Effects (RWU 4403)
Colin Hardy, Research Forester, Fire Behavior (RWU 4401)
Albert R. Stage, Project Leader, Quantitative Analysis (RWU 4154)
Nicholas L. Crookston, Operations Research Analyst, Quantitative Analysis (RWU 4154)

In an effort related to wildlife needs, a meeting was held September 28-29, 1993 at Priest River Experimental Forest to review general issues concerning Wildlife Habitat Modeling and the FVS. A follow-up meeting was held in Portland the first week of December 1993 to discuss integration of snag dynamics into FVS. Meeting notes from both meetings are available from Richard Teck, USDA Forest Service, Timber Management Service Center, 3825 E. Mulberry Street, Fort Collins, CO 80525.

The scoping meeting to initialize the current FVS-Fire modeling project was held as a conference call on May 18, 1995. Participants included: Jim Brown, Nick Crookston, Elizabeth Reinhardt, Al Stage,

Richard Teck, and the ESSA project team (Werner Kurz, Sarah Beukema, Julee Greenough, and Don Robinson). This meeting clarified the direction and objectives of the project, and prepared for a model design workshop.

The model design workshop took place at the Fire Lab in Missoula on June 15-16, 1995. Participants included: Bob Burgan, Jim Brown, Nick Crookston, Kendrick Greer, Colin Hardy, Mike Larsen, Rich Lasko, Elizabeth Reinhardt, Eric Smith, Al Stage, Richard Teck, and the ESSA project team (represented by Werner Kurz, Sarah Beukema and Julee Greenough). The meeting refined the scope of the model and determined the best approach to use in the development of each submodel.

A model review workshop occurred in Portland on October 17-18, 1995. Many previous participants (Jim Brown, Nick Crookston, Colin Hardy, Elizabeth Reinhardt, Eric Smith, Al Stage, Richard Teck, Werner Kurz, and Sarah Beukema) and some new ones (Lance David, Dick Holthausen, and Bob McGaughey) were present. This meeting reviewed the designed and behavior of the model and suggested refinements and ideas for future work.

2.0 Scope of the FVS-Fire Model

The FVS-Fire model provides information on the intensity with which fires would be likely to burn if they occurred at different times over the course of stand development. When requested by the user, the model also simulates the impact that those fires would have on stand development and fuel loads. The model does, however, estimate the probability of a fire event or attempt to predict when fires will occur. The following sections describe the scope of the model in more detail.

2.1 Spatial Extent and Resolution

The spatial extent of the FVS-Fire model is from 1 to 1000 stands (each of which is assumed to be between 1 and 50 acres in area), and the resolution will be one stand. Spatial variability within stands will be handled statistically. This fire model will be part of the Parallel Processing Extension (PPE) of the Prognosis Model (Crookston and Stage 1991). A version will also exist that has the spatial extent of one stand and is linked to the single stand (standard) FVS.

2.2 Temporal Extent and Resolution

The temporal extent equals that in the FVS, about 300 to 400 years. The resolution will be annual.

2.3 Management Actions

All standard FVS management actions (*e.g.*, harvesting and thinning) remain available when the fire model is active, and the fire model keeps track of the fuel changes resulting from these management activities. In addition, the fire model provides several new management actions such as prescribed burns and treatments aimed at manipulating the amounts of fuel present in the stand. These new management actions are described in the following subsections. Note that wildfires may be simulated in precisely the same way as 'free-burning' prescribed fires; the behavior of a fire within a stand does not depend on its origin.

2.3.1 Fires

The user can simulate the impact of a fire by specifying the year when the fire is to occur and the stand in which it occurs (if the simulation is running with more than one stand). If they choose to do so, the user may also specify other characteristics of the fire, including any or all of the following:

- the conditions under which the fire occurs, including:
  - fuel-moisture conditions at the time of the fire,
  - wind speed,
  - ambient air temperature at the time of the fire, and
  - the season in which the fire occurs (Spring, Summer or Fall);

- the type of fire (free-burning, throttled-back, or mass-ignition; see Section 4.3);
- the percentage of the stand area where crown fire occurs during the burn; and
- the flame-length that occurs during the burn, if the user wishes the override the value calculated by the model for the fire characteristics that have been specified (see Section 4.4).

The fire characteristics chosen by the user will affect the model's estimation of fire intensity and fire effects.

2.3.2 Harvest Methods

The user will be able to specify that harvesting or thinning is done by any one of the following four methods:

1. Ground based (including cat skidding and line skidding),
2. High lead (including skyline), or
4. Precommercial or helicopter.

"Whole tree removal" will be an option under each of the above harvest methods.

In the model, the harvest methods above are distinguished by their effect on the fuel depth remaining after harvesting. The user may either accept the model's default calculations of fuel depth following harvesting by one of the specified methods or may specify their own multiplier.

The amount and condition of dispersed fuels will affect the model's estimation of other fuel parameters (Section 4.2.3), and its calculation of fire intensity.

2.3.3 Snag Creation and Slashing

Artificial snag creation requires that trees are killed but left standing. 'Slashing' refers to the felling of trees that are then left in the stand. A new harvest keyword in FVS (YARDING) allows the user to simulate both of these treatments, by specifying whether the selected trees are felled when they are killed, and whether felled trees are removed from the stand.

2.3.4 Slash Treatments

The user will be able to specify any of the following slash treatments in the model:

1. Trampling / crushing / chopping / chipping,
3. Flailing / lopping,
4. Pile and burn, or
5. Jackpot burning.

As was the case for the harvest methods discussed above, these treatments will be distinguished in the model by their effect on fuel depth (for cases 1 and 2) or fuel levels and other parameters (for cases 3 and 4). The user may either accept the model's default values for the specified slash treatment, or may enter their own values for any or all of the parameters.

2.4 Indicators

Indicators are the model outputs which allow users to make judgements about the behavior of the model or to evaluate different management options. These indicators are printed in a variety of reports, each representing different parts of the model. These reports may be printed during runs with the Standard FVS (single stand), or during a PPE simulation. In many cases, users can select the frequency to print the information, and in all cases, the reports can be printed without headings if desired. No reports are printed by default; keywords must be used to request any fire-model-specific output.

2.4.1 Snag Report

The user may request that an optional snag list is output for some or all stands at specified times (*e.g.*, annually, at periodic intervals, or in one particular year). The report includes only those snags that are still standing in the year that reporting is requested. The report provides the following information on every snag record (group of similar snags) in the selected stands:

1. *Year.* The year in which the snag record is being reported.
2. *Stand.* The stand in which the snag record occurs.
3. *Species.* The tree species of the snag.
4. *DBH class.* Snags may be aggregated into up to 6 diameter classes specified by the user (subject to the requirement that the diameter classes be bounded by even numbers).
5. *The average diameter* at breast height, at the time of death, of all the snags aggregated in this record.
6. *Current height* of the snags in the record. This is reported separately for the hard and soft snags in each record.
7. *Volume* of the snags in the record, estimated from the current height and the diameter at the time of death. The volume of the hard and soft snags in each record is reported separately, and a total is provided.
8. *Year of death.*
9. *Snags/acre*. The number of hard and soft snags per acre that are represented by this snag record, and the total number of snags per acre in the record.

2.4.2 Potential Flame Length Report

At the user's option, the potential flame length under different wind and moisture conditions will be output for every stand at specified times (*e.g.*, annually, at periodic intervals, or in one particular year). This report gives an indication of what could happen under various conditions, allowing managers to weigh the costs and benefits of fire prevention measures, controlled burns, *etc.* For additional information, the report also gives the small and large fuels in the stand and the static fuel model which was chosen. The report has the following format:

		Potential flame length (feet)				Fuels		
Year	Stand	Very low moisture & 20 mph winds	Low moisture & 10 mph winds	Moderate moisture & 5 mph winds	High moisture & no wind	<3"	>3"	Model

2.4.3 Fuel Report

The user may also request an option report on the fuels status in every stand at specified times (*e.g.*, annually, at periodic intervals, or in one particular year). This report has the following format:

		Surface fuels (tons/acre)										Standing wood (tons/acre)							
		Dead							Live			Dead		Live					
Year	Stand	Litter	Duff	0-3"	3" +	3-6"	6-12"	12" +	Herb	Shrub	Total	0-3	3+	Foliage	0-3	3+	Total	Total fuels	Fuel Consumption

2.4.4 Landscape Status Report

The user may also request that reports summarizing conditions across the landscape as a whole can be output every FVS year. The three reports provide the following information:

1. The percent of the landscape in different *total* surface fuel load-classes (0-10 tons/acre, 10-20 tons/acre, 20-30 tons/acre, and >30 tons/acre), for fuels above and below 3" in diameter, all woody fuels, duff, and snags (*e.g.*, for fuels below 3" in diameter, the number of acres with 0-10 tons/acre, 10-20 tons/acre, 20-30 tons/acre, and >30 tons/acre).

2. The percent of the landscape in different fuel models.

3. The percent of the landscape in different potential flame length categories. This report gives the percent of the landscape that would have flame lengths less than 4 feet, greater than 4 feet or greater than 8 feet for each of the different moisture levels.

2.4.5 Fire Event Reports

The following reports are printed only in the event of a fire:

1. *Burn Conditions and Fire Behavior Report*
   - year, stand, moisture of each class of fuel (1 hr, 10 hr, 100 hr, duff + 1000 hr, and live herbs + shrubs; see Section 4.2 for explanation), wind, slope, fuel model, flame length, and crown scorch height. Note that the fuel model, flame length, and crown scorch height are the only computed variables in this report; the rest are parameters that are controlled by the user.

2. *Fuel Consumption and Physical Effects Report*
   - year, stand, mineral soil exposure, fuel consumption (by fuel component, as listed in the fuel report), percent consumption of duff and of fuels larger than 3 inches, percent of trees with crowning, and smoke production (the tons of particulate matter released that are < 2.5 and < 10 microns in diameter).

3. *Tree Mortality Report*
   - year, stand, tree species, percent mortality by 2" diameter classes. The final row for each stand gives the total percent mortality in each size class.

3.0 Overview of Model Structure

3.1 Submodels

Six submodels combine to create the FVS-Fire model. The following four submodels are always active when the model is run:

1. FVS (single or multi-stand version; Stage 1973, Crookston and Stage 1991) for simulating the growth, mortality, and management of the trees in each stand.

2. A Snag model for tracking, decaying, and falling standing dead trees.

3. A Fuels model, which will incorporate:
   a) a Woody Debris model for tracking the accumulation and decomposition of downed wood and litterfall; and
   b) standard fuel models for the estimation of grass, forb and shrub quantities, and other fuel parameters.

4. A Burn model, which will incorporate:
   a) the FIREMOD routine from FIRESUM (Keane *et al.* 1989), for the calculation of fire intensity;
   b) a Fire Effects model (*e.g.*, tree mortality, crown scorch, fuel consumption, and mineral soil exposure); and
   c) a Smoke Production model for calculating the amount of smoke produced from the consumed fuels.

The remaining two submodels are ones which are not required (*i.e.*, they may be present, but not activated in a particular model simulation). These models are:

5. A Fuels Management model for performing management activities which are not part of FVS.

6. The Westwide Pine Beetle Model (PBM; Beukema et al. 1994), for simulating the impact of pine beetles on the landscape (when the multi-stand version of FVS is in use).

Some of these submodels are existing models which were modified and brought together in the FVS-Fire model (*i.e.*, FVS, PBM, FIREMOD, and fire effects), and others are ones which were newly created for the FVS-Fire model (management models, woody debris model, non-woody vegetation).

3.2 Submodel Interactions

Figure 3.1 illustrates the general scheme of the FVS-Fire model. The model uses the tree-list information in FVS and information about management actions to simulate the amount of slash and woody debris above and below 3" in diameter that is present in the stand. These two debris values,

along with the habitat type of the stand and the management history of the stand, will be used to select the standard 'fuel model' most appropriate to the stand. Each standard fuel model describes in more detail the load of each of the smaller size classes of fuel that is expected in the stand, and other characteristics of the fuel (described in Section 4.2.3 below). It is the fuel information from these standard fuel models that are combined with the fuel moisture data, wind speed, slope and burn type (free-burning, throttled-back, or mass-ignition; see Section 4.3) to predict the flame length that would occur during a burn. Finally, the predicted flame length is combined with wind speed, temperature and season information - and the FVS-Fire model's dynamic predictions of debris, duff, and litter loads - to calculate the effects of the fire (*i.e.*, fuel consumption, smoke production, tree mortality, percent mineral soil exposure, *etc.*).

The "looking outward matrix" on the next page illustrates the interactions between specific submodels in more detail. Each cell in this matrix describes the information that is passed *from* the submodel in the row *to* the submodel in the column. The cells on the diagonal describe the main activities of each submodel.

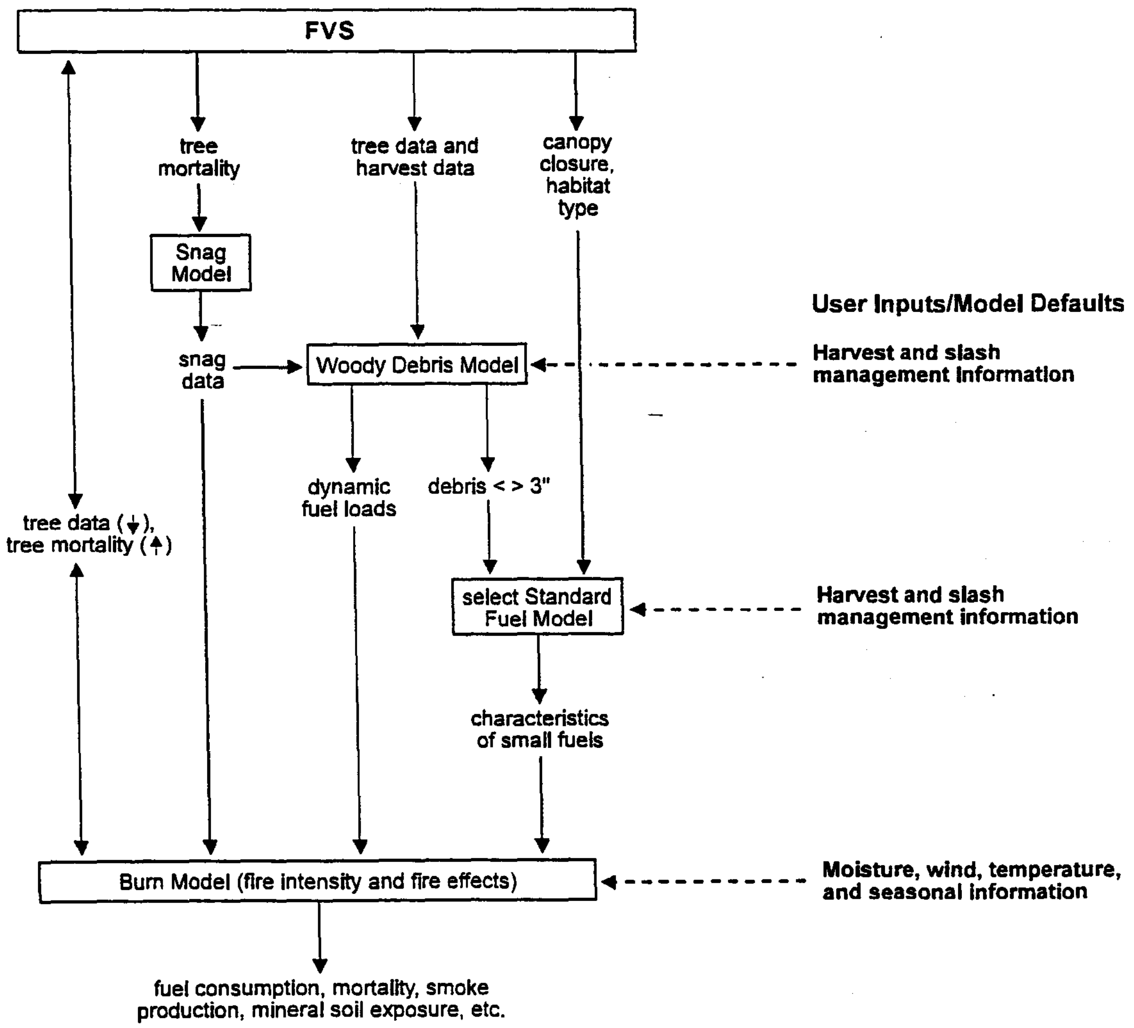


Figure 3.1: Scheme of the FVS-Fire Model. The boxes in this figure show the main sources of information - submodels or user-inputs - employed in the model. The arrows indicate the flow of information between submodels. See text for further explanation.

To / From	FVS	PBM	Snag	Fuels	New management options	Burn
FVS	Growth, mortality, regeneration and management	Host tree list	Mortality (size, sp, cause)	Tree and snag lists (for litterfall), Trees cut (for slash), habitat type, canopy cover		Tree list (ht, sp, dbh, crown length), Density, Slope
PBM	Tree mortality	Beetle dynamics and impacts	Salvage logging	Windthrown		
Snag		Vol/acre of new snags (for Ips)	Falldown and decay	Snags falling, remaining snag list (for litterfall and breakage)	# per acre (for event monitor)	
Fuels		Tons/acre of new woody debris (<3", for Ips)		Decay and conversion to duff of woody debris & litterfall, amounts of herbs and shrubs.	Amounts of debris and understory vegetation per acre (for event monitor)	Amount and bulk density in each fuel size class
New management options			Snag removal / creation	tree felling and removal, slash management actions	Modify dead wood and understory vegetation pools, Trigger burns	Occurrence of burn
Burn	Mortality, Crown length, Mineral soil exposure	Scorched trees (crown removal class) Trees removed (for brood reduction)	Trees killed, snags burned	Amount consumed	# per acre of trees killed, for event monitor to trigger salvage logging	Calculate fire intensity and impact [Inputs: moisture, wind, fire type]

4.0 Submodel Descriptions

This section describes how snags, fuels (consisting of woody debris, herbs, shrubs and duff), fire intensity and fire effects are modeled in the FVS-Fire model. The FVS model and the Westwide Pine Beetle model are described elsewhere (Wykoff 1986, Crookston and Stage 1991, Beukema *et al.* 1994).

4.1 Snags

Ideally, the snag model could become an independent extension in FVS/PPE. The snag model can potentially interact with other models such as the pine beetle model.

The snag model tracks the fate of standing dead trees in the model. Trees become snags through various management options, including snag creation, and through natural mortality of the trees due to competition, fires, or other causes. Snags are represented in the model using the treelist format, with each 'record' representing a group of trees of the same species that died in the same FVS cycle and are in the same diameter-, and height-class (*i.e.*, a single snag record is kept for each different species-, diameter- and height-class combination of snag that is created in a given FVS cycle). The snags in each record are described by the following seven characteristics:

1. Diameter class. The snags are grouped into two-inch diameter classes according to their diameter inside the bark. The largest class is those trees with an inside bark diameter of 36" or more.

2. Species. The species of tree from which the snag originated.

3. Height. Each record contains the average height of the trees in that record, both at the time of death and currently (for the initially-hard and initially-soft snags separately; see item 5 below). If the trees in a record have very different initial heights (greater than 20 feet different), the record is divided into two different height classes. This allows the model to follow these height differences in its subsequent simulation of snag dynamics.

4. Age. Each record maintains the age of the snag (i.e., time since the death of the tree).

5. Decay status. By default, newly created snags are assumed to be 'hard' in the model. Over time, these snags decay until eventually they are considered 'soft'. At the user's option, a proportion of all newly created snags may be considered to be soft from the time of death; these snags will experience more rapid height loss in the model. Debris from breakage or falling of any soft snags decays faster than debris from hard snags.

6. *Cause of death.* *Ideally, the cause of death would be known and would affect falldown rates. Tentative causes of death are 0=unknown, 1=fire, 2=beetles. An additional variable could be used to indicated whether the snag was root diseased at the time of death. At the present time, however, there is no cause-of-death information in the model.*

7. Stems per acre. The number of stems per acre represented by this record.

Notice that only four of the characteristics will change over time (age, decay status, height, and stems per acre). The simulated change in height as snags age allows the corresponding reduction in volume to be calculated (using the diameter at time of death). If the number of snags in a particular record falls below a minimum value, the record is considered to be empty. Such emptied records are used to store information on newly created snags.

Falldown Rates

The falldown rates in the snag model vary between different species and diameter classes. Falldown rates for each species are calculated relative to a standard, 'reference' species. The standard fall rates apply to ponderosa pine, when the default parameter values are in use in the model. The standard falldown rates are based on a linear approximation of Bruce Marcot's data for eastside ponderosa pine snags. The linear relationship is modified so that the last 5% of all snags over 18 inches will not have all fallen until they are 100 years old. Snag species that are considered to fall slower than ponderosa pine (white pine, western larch and Douglas-fir) have falldown rates which are 10% less than the standard rates, while species that are considered to fall faster (grand fir, western redcedar, western hemlock, lodgepole pine, spruce and alpine fir) have falldown rates which are 10% greater than the standard rates. Scaling values for all species are under the user's control, as are the persistence times for the last 5% of snags.

Note that, according to Marcot's data and also in this model, the rate at which snags fall does not depend on their age (except that, in the model, the last 5% of large snags may fall more slowly). Since no data were available on whether hard snags fall at a faster rate than soft snags, the rate of snag fall in the model does not depend on snag decay state.

The falldown rates just described are modified after a fire. If a threshold scorch height has been exceeded during the fire, all soft snags will fall within 7 years, and 90% of hard snags below 12 inches in diameter will fall in the same time period. Large, hard snags are unaffected. All of the parameters just mentioned are under user-control.

Decay Rates

The rate of decay of initially-hard snags depends on their diameter at the time of death, and is based on a linear approximation of Bruce Marcot's westside Douglas-fir data (as is the rate of decay in his eastside model). The relationship is scaled up or down by 10% for snags that are considered to decay faster or slower than the standard set by Marcot's data (which is applied to ponderosa pine under the default parameter values in the model). Scaling values for all species are under the user's control.

Height Loss

The 'standard' rate of height loss (breakage) of snags in the model is such that 50% of the initial height is lost in the first 30 years (i.e., 2.28% per year). After this, the rate of height loss is 1% per year. Snags that are considered to break apart faster or slower than the standard rate lose height at a rate which is 10% faster or slower, respectively, than that rate (which is applied to ponderosa pine under the default parameter values in the model). Scaling values for all species are under the user's control.

Snags which are initially-soft lose height at twice the rate of initially hard snags, until they reach 50% of their initial height. This scaling value is also under user control.

Initialization

Snags are initialized from the treelist, and are currently assumed to have died in the inventory year. All snags initialized in this way are considered to be hard snags, unless the user has specified that a proportion of the snags created during simulation are initially-soft. Then, the user-specified proportion is applied. A keyword allows users to enter additional snags manually if inventory information is available (similar to the STREAD keyword in the root disease models).

Management

Various standard FVS management options may create snags. A new FVS keyword allows users to tell the model, each time management is done, how many snags are left standing (by species and size). A fire model management option allows users to remove snags from a stand. *Some of the snag characteristics (diameter, species group, age, decay class) will be made available to the 'Event Monitor' in FVS, in order to allow users to manage stands for target levels of snags.*

4.2 Fuels

'Fuels' include dead wood on the forest floor (woody debris), litter, duff (here taken to include both humus and brown cubicle rot), and live shrubs and herbs. For the purpose of predicting fire intensity and impact, it is not necessary to distinguish sizes of woody debris greater than 3 inches in diameter. However, the model considers debris in larger size classes (3-6", 6-12" and >12") as the information is of interest for wildlife managers and other potential users. Note also that amount of aggregated (piled / lined) and dispersed debris in each size class will be modeled separately.

As described in Section 3.2, the FVS-Fire model uses two distinct sources to obtain information about the fuels present in each stand. The first source is dynamic simulation of the fuel loads. The Woody Debris model takes tree growth, mortality, and management information from FVS and uses it to estimate the amounts of debris and litter produced in the stand in each time period. The debris model then simulates the rates of decay and conversion to duff of this material, so that it has at all times a dynamic estimate of the amount of debris (of different sizes), litter, and duff in the stand. The FVS-Fire model uses these dynamic estimates to calculate fuel consumption and smoke production, and to select an appropriate standard fuel model for the stand (as explained immediately below).

For the purpose of predicting fire intensity (flame length), the FVS-Fire model uses a second source of information: standard fuel models. The Woody Debris model's dynamic estimates of the amount of debris above and below 3" in diameter, and some FVS data about the stand (canopy closure, habitat type, and management history) are used to select the standard fuel model most appropriate to the stand. The selected fuel model provides detailed information on the characteristics of small fuels (see Section 4.2.3), information which FIREMOD requires to calculate the expected fire intensity. The standard fuel model also provides an estimate of the amount of live herbs and shrubs in the stand, which is used in the calculation of fuel consumption and smoke production. Alternatively (and by default), the necessary information can be gathered using a series of equations which provide more continuous approximation of the parameter values (see Section 4.2.3).

The following sections describe the estimation of fuel loads and characteristics in more detail.

4.2.1 Woody Debris, Litter and Duff

Inputs to the woody debris classes in the model will come from five sources. One is the occasional loss of some parts of the tree canopy, from breakage due to snow or wind, or from disease. The model simulates this source of debris by adding a small, constant proportion (1%) of each crown component to the debris classes each year. The total amount of crown material in each debris size class is estimated using the equations in Brown and Johnson (1976), except that equations for similar species were sometimes substituted where information for a particular crown component was missing for other species.

The second source of woody debris in the model is that, as the crown lifts (as the tree grows), the lower branches die back and eventually fall. This is simulated by adding a fraction of the total crown material in each size class to the debris classes. The fraction is approximated from the ratio of 1) the height that the crown lifted between the previous cycle, to 2) the total length of the crown in the previous FVS cycle. A constant proportion of this fraction of material is transferred to the debris pools in each year that the fire model simulates in the current FVS cycle.

The third source of woody debris in the model is from tree harvesting. The volume of unmerchantable felled trees, and the crowns from cut trees, is added to the appropriate debris pools. The model varies its assumptions about how much of this material is left in the stand and the manner in which it is aggregated depending on the harvest techniques and slash management treatments specified by the user (see Section 2.3). FVS wood volumes are converted to 'dry tons' of debris by multiplying by a species-specific density values (Brown *et al.* 1977).

The fourth source of woody debris in the model comes from snags. The rate of debris inputs from the crowns of snags is estimated from available data on the amount of foliage, twigs and limbs remaining five years after death, as shown in the Table 4.1. Debris inputs due to breakage of the bole are modeled dynamically as snags break and fall. The timing of these debris inputs is of much less consequence to model behavior than is their volume.

A fifth potential source of woody debris in the model comes from the scorched parts of crowns on trees that are still living. When a crown has been scorched up to a certain height by fire, all of the un-burned crown material below that height is assumed to be dead wood that will fall (*i.e.*, be added to

debris pools) over succeeding years in the same manner as was just described for the dead branches on snags.

Table 4.1: Rate of crown loss for snags of different species. The information on the amount of each crown component remaining 5 years after death is taken from [AL: what is this reference, for the data you sent us?]. '-' indicates where this reference provides no specific information. The 'estimated time to 100% loss' will be used to calculate a constant rate of loss in each year (*e.g.*, 100% loss in 10 years will mean that 10% of the original canopy is added to the debris pools each year).

Snag Species	Amount remaining 5 years after death:				Estimated time to 100% loss (years):			
	Foliage	Twigs	Branches	Large Limbs	Foliage	Twigs	Branches	Large Limbs
White pine	0%	< 75%	-	'numerous' limbs gone	5	15	15	15
Ponderosa pine	0%	<50%	<50%	'falling'	5	10	10	10
Spruce	0%	<30%	<50%	'falling'	5	10	10	10
Douglas-fir	0%	<50%	<75%	'falling'	5	10	15	15
Western hemlock	-	-	-	-	5	10	15	15
True firs	0%	<50%	<75%	'falling'	5	10	15	15
Grand fir	-	-	-	-	5	10	15	15
Subalpine fir	-	-	-	-	5	10	15	15
Western larch	-	-	-	-	5	10	15	15
Lodgepole pine	0%	<75%	<75%	-	5	15	15	15
Western redcedar	0%	<60%	-	'some' limbs falling	5	15	20	20

Litterfall in the model is derived from foliage loss from snags (as described) and the annual foliage litterfall from trees, which is the major source of litter in most stands. The model calculates annual litterfall for each tree such that 100% of current foliage is expected to fall in the period of time which is the usual foliage lifespan of foliage for that tree species (i.e., annual litterfall = current foliage weight / foliage lifespan). Data on foliage lifespan were taken from Keane *et al.* (1989).

Inputs into the duff fuel class in the model will come only from the conversion of material in the woody debris and litter classes. The model uses a single duff-conversion rate for all sizes of woody debris and litter.

The model simulates decay of the woody debris pools by leaching and microbial respiration, and does not model the physical fragmentation of debris into smaller pieces. Coarse woody debris, litter and duff are all decayed by removing biomass using a simple exponential decay process that removes a constant proportion of the biomass each year. The decay rates for coarse woody debris are taken

from coefficients presented in Table 3 of Harmon *et al.* (1986). Because this table is based on the compilation of data collected by other authors, it was necessary to combine some of the repeated values for same-species observations, giving more emphasis to studies spanning longer periods. It was also necessary to assign values to some missing species based on their similarity to other species. We have combined these results and assigned each species of the Northern Idaho variant to one of four decay rates (Table 4.2). Since there is a fairly narrow range of observed decay rates, it might be justifiable to simplify the model by reducing the number of decay rate classes for coarse woody debris.

Table 4.2: Default decay rates for the woody debris of different species.

Species code	Species name	Default annual decay rate
1	white pine	0.012
2	western larch	0.011
3	Douglas-fir	0.007
4	grand fir	0.011
5	western hemlock	0.010
6	western red cedar	0.010
7	lodgepole pine	0.012
8	engelmann spruce	0.010
9	subalpine fir	0.007
10	ponderosa pine	0.012
11	other	0.012

The model keeps track of the so-called "hard" and "soft" origin of the decaying material, and assigns "soft" material a decay rate that is 10 percent higher than the "hard" decay rates shown in the preceding table.

The decay rate for litter is 0.5/yr, which removes half the litter biomass each year. Duff is an intermediate decay product for both coarse woody debris and litter. The model simulates the creation of duff by allocating twenty percent of the predicted biomass loss of the litter and coarse woody debris categories to the duff category, leaving the remaining eighty percent to "disappear" as a result of microbial decay and leaching. Duff, in turn, decays at the very slow rate of 0.002/yr.

Users can change the any of these decay rates and the proportion of the decayed material that goes into duff. Piled fuel is assumed to decay at the same rate as unpiled fuels.

The fuel classes that the FVS-Fire model simulates dynamically are initialized at the start of each simulation. Data from thousands of National Forest plots are used to determine default initial values

for each fuel class (Jim Brown, pers. comm.). Users also have the option of over-riding the default values and specifying their own initial values for each class.

4.2.2 Live Herbs and Shrubs

Under the modeling scheme described in Section 3.2, the amounts of herbs and shrubs in the stand will be 'constants' obtained based on the quantities of live fuels in the initial conditions for different cover types. One reason that the FVS-Fire model does not simulate herbs and shrubs dynamically is that the total fuel load of these materials is felt to be roughly constant in a stand (after canopy closure): understory herbs grow back within one year of a fire to greater volumes than they had before the fire. In terms of fuel load, the rapid increase in herb biomass will compensate for the more slow increase in shrub biomass. Although the species composition of herbs and shrubs may change as a result of fire, herbs and shrubs are not a major determinate of fire dynamics, so refined understory modeling is not justified in the initial development of the FVS-Fire model. The amounts of herbs and shrubs in the stand only influence smoke production values. The only exception to this may be in the first 20 years of stand development, when herbs and shrubs may be a large portion of the total fuel load in the stand, but stands will not usually burn at this time.

4.2.3 Selection of a Standard Fuel Model

Traditionally, a series of standard fuels models have been used to calculate a series of parameter values used in the fire intensity calculations. Fuel models were selected based on the amount of large and small fuel in the stand (fuel above and below 3" in diameter) and management history. The benefit of this approach is that the standard fuel models are well understood and are trusted. At a workshop, however, participants realized that the fact that parameters change at the boundary between fuel models (which may lead to large changes in fire intensity) could lead to misleading results. For example, fuels could change a large amount and not affect fire intensity if the fuel levels were far from a boundary between fuel models, or fuel levels could change a very small amount and greatly change fire intensity. It was then decided that a dynamic approximation would be used to determine each of the parameter values based on the same factors as before (small and large fuels, habitat type, and management history). This approximation was determined by doing a series of nonlinear regressions based on the information in the standard fuel models. These dynamic parameter approximations are used by default in the model.

The parameters values chosen using either the static or dynamic fuel model calculations are:

- load (in oven-dry tons per acre) of different fuel sizes: 0.00-0.25", 0.25-1.00", 1-3", and "live";
- average surface/volume ratio of the pieces of debris;
- depth; and
- moisture of extinction.

4.3 Burn Model

4.3.1 Burn Conditions

Depending on the user's specification, fires may be any one of the following types:

1. *Free-burning* fires are those that are established and 'free to burn'. The flame length of a free-burning fire depends only on the amount of fuels available, the slope of the site, and environmental conditions at the time of the fire. Free-burning fires may be either:
   a) prescribed free-burning fires, or
   b) wildfires.

   All wildfires are free-burning fires.

2. *Throttled-back* fires are prescribed burns that are confined to thin strips. The flame length of throttled-back fires will generally be less than that of a free-burning fire under the same fuel, wind and moisture conditions.

3. *Mass-ignition* fires are prescribed burns with numerous ignition points. The flame length of mass-ignition fires will usually be greater than that of a free-burning fire under the same conditions. Mass ignition fires are used to achieve complete stand replacement.

In the model, free-burning, throttled-back, and mass-ignition fires are distinguished by applying an appropriate scaling factor to the flame length predicted by FIREMOD. By default, the model reduces the flame length to 70% of the expected free-burning flame length when the user specifies a throttled-back fire, and increases the flame length to 200% of the free-burning value when the user specifies a mass-ignition fire. The user may, if they prefer, use one of the model keywords to specify either the flame length or the flame scaling factor to be used instead of choosing one of the three pre-defined fire types.

If they wish, the user may also specify the conditions under which the fire occurs, including any or all of the following:

- fuel-moisture conditions at the time of the fire. These may be described either by entering a separate value for each fuel class (0-0.25" / 1 hour fuels, 0.25-1" / 10 hour fuels, 1-3" / 100 hour fuels, duff & >3" fuels, live herbs, and live shrubs), or by choosing a pre-set 'burn condition' (i.e., 'very-dry', 'dry', 'moist', or 'wet').
- the wind speed. In the case of wildfires, the user may either specify an exact wind speed, or request the model's 'high', 'medium', or 'low' default wind speeds (20, 10 or 4 miles/hour, respectively). If no selection is made, the model will use the 'high' default wind speed. In the case of prescribed fires, the model will assume a default wind speed of 6 miles per hour unless this value is over-ridden by the user. Regardless of which way a wind speed is chosen, the model will assume that the specified value is the wind speed at twenty feet above ground level. It will then convert this value to the expected mid-flame wind speed by multiplying by a correction factor appropriate to the level of canopy closure in the stand at the time of the fire. The correction factor will be determined as shown in Figure 4.1.

- the ambient air temperature at the time of the fire. By default, the model assumes a temperature of 70° F.
- the percentage of the stand where crowning occurs during the burn. If this is not specified, the model assigns a default value based on the percent canopy closure in the stand and fuel moisture conditions at the time of the burn. The model then assumes that all of the foliage in this area is consumed in the fire, as well as 50% of the crown material that is less than 0.25" in diameter. None of the larger crown material will be consumed. Trees that experience crowning will die.

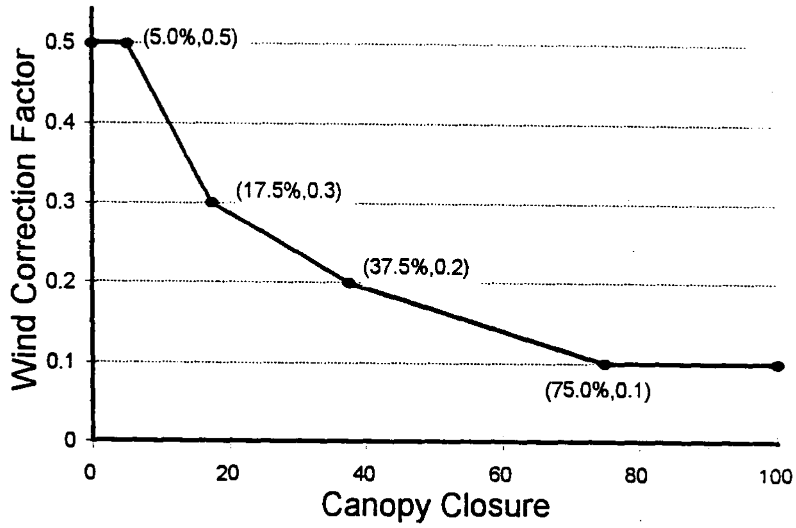


Figure 4.1: Wind Speed Correction Factors. Mid-flame windspeeds are estimated by multiplying the wind speed at twenty feet by a correction factor that depends on the percent canopy cover in the stand, as shown in the figure.

4.3.2 Fire Intensity

Fire intensity is calculated using the existing FIREMOD (in Keane *et al.* 1989) model.

4.3.3 Fire Effects

Tree mortality is calculated based on scorch height, crown length, dbh, and species. Fuel consumption is calculated based on the type of fuel (natural or created, piled or unpiled), and moisture levels. Litter and live herbs are always 100% consumed and shrubs and 'regen' are 60% consumed. As described in Section 4.2.1, any unburned material in the scorched portion of the crowns of trees that are still alive is considered to be dead wood, and will subsequently be added to the woody debris pools. When a tree's crown has been scorched in a fire, its crown ratio is reduced and growth is slowed for a period of time after the fire.

Smoke is produced by multiplying the tons of fuel consumed in each class by an emission factor which may vary with moisture level and piled/unpile designation.

In the case of prescribed pile-and-burn fires, some live trees may be killed in the portion of the stand that is covered by piles. The number of trees killed is defined by the user.

5.0 Model Behavior

5.1 Introduction

This section summarizes the results of preliminary analyses of the behavior of the new FVS-Fire model. The model runs were done using the PPE in the Inland Empire variant of FVS. Runs were conducted using nine stands selected from the Nez Perce National Forest. The basal area and density distribution by species and 5-inch dbh size class of each stand is shown in Figure 5.1 while other stand information is summarized in Table 5.1. Stands were selected to represent a diversity of species and site conditions.

Table 5.1: Stand attributes for each of the nine stands used in the simulation.

	Stand Number								
	1	2	3	4	5	6	7	8	9
Elevation (ft)	4800	5300	5400	5400	5300	5300	5600	4800	4800
Slope (%)	30	20	30	0	30	0	30	0	30
Aspect	SW	E	N	N	NW	NW	NW	N	N
Area (acres)	13	6	26	30	32	32	9	15	10
Density (trees/ac)	399	114	263	269	122	122	1432	167	167
BA (sq ft/ac)	67	144	244	239	69	66	168	105	105
QMD (in)	5.6	15.2	12.3	12.2	10.2	10.0	4.6	10.7	10.7
Dominant Species	PP	GF	GF	GF	GF	GF	LP	DF	DF

Two different scenarios were simulated on subsets of the stands. Both simulations started in 1990. In the first (Section 5.2), using five of the stands, fires were simulated in 2040 and 2140. In the second (Section 5.3), using the remaining four stands, one fire occurred in 1995 and the simulation continued without further fires for the next 180 years.

The output is presented in a consistent manner for all stands. In all cases, the output for each stand consists of two pages of graphs. The first gives stand attributes while the second concentrates on output specific to the fire model. The graphs are (from left to right, by row):

Page 1:

BA	the basal area of all live trees in the stand (sq. ft./acre).
QMD	the quadratic mean diameter of live trees (inches).
NOTREES	the density of live trees in the stand (number of trees/acre).
TOTVOL	the total volume of live trees in the stand (cu.ft./acre).

FOLIAGE	the total foliage weight of live trees in the stand (tons/acre). Note that this is calculated by the fire model.
MORT	the total volume loss per year from all causes, including fire (cu.ft./acre/year).

Page 2:

Snag density	the density of snags (standing dead trees) in the stand (snags/acre). SDG12 is the density of snags greater than 12 inches dbh, while SDL12 is the density of snags less than 12 inches dbh.
Snag vol	the total volume of snags in the stand (cu.ft./acre). SVG12 is the volume of snags greater than 12 inches, while SVL12 is the volume of snags less than 12 inches.
Debris	the down, dead fuels (litter, duff, and woody fuels other than snags). PLUS3 is the sum of all pools greater than 3 inches, while LESS3 is the sum of the pools less than 3 inches (0-.25, .25-1, 1-3).
Flame length	the potential flame length which could occur given the slope, current canopy closure, current fuel levels and four different moisture conditions. This is calculated every 10 years.
PERCENT	the percent of trees in different size classes which died when a fire occurred. Empty bars are for classes which contain no trees. The classes are 2-inch dbh classes. In scenarios with two fires, the first graph represents the mortality distribution in 2040 and the second represents 2140. In scenarios with one fire, the graph represents the mortality in 1995.

Note that the maximum y-axis values on the graphs vary between stands.

All scenarios were simulated for 180 years, with FVS running on 5-year time steps (a cycle) and the fire model running on annual time-steps. In each stand in each cycle, if the basal area of the stand was less than 150 sq.ft./acre, 50 trees/acre of the dominant species (as listed in Table 5.1) were planted. One cycle (five years) after a fire, 400 trees/acre of the same species were planted, independent of stocking levels or mortality. The automatic regeneration model was turned off for these simulations to make it easier to determine what species were present in the stand and when new trees were planted.

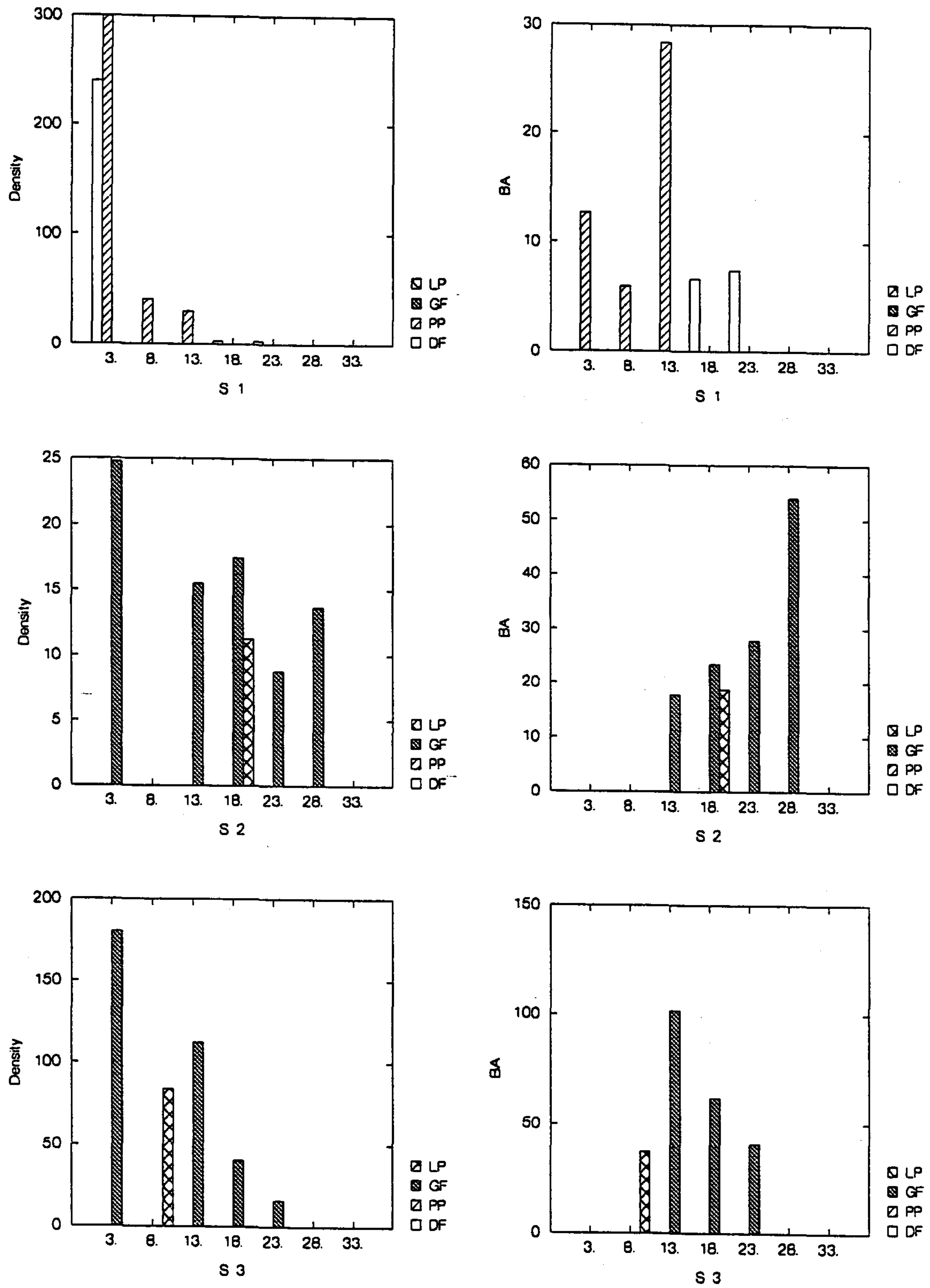
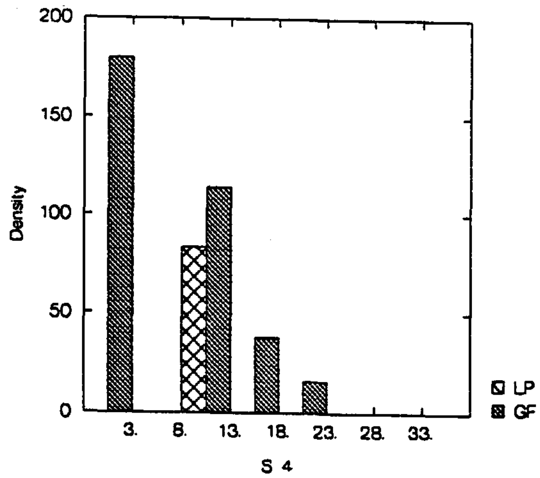


Figure 5.1: Density and basal area distributions by stand, species, and size class for each stand. Size classes are 0-5 inches, 5-10 inches, 10-15 inches, 15-20 inches, 20-25 inches, and greater than 30 inches.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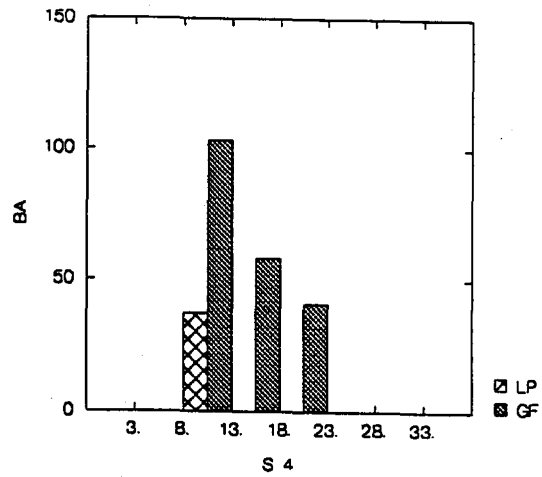
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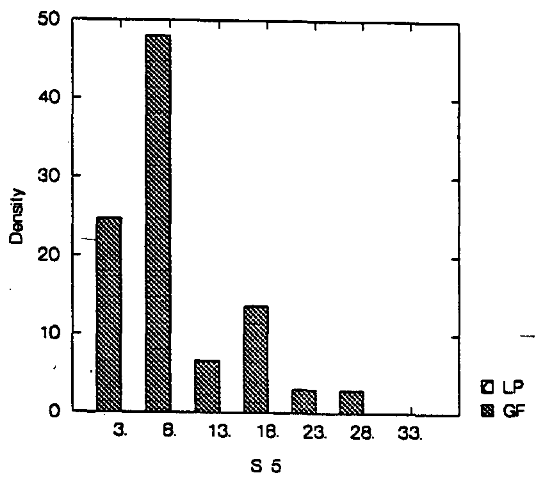
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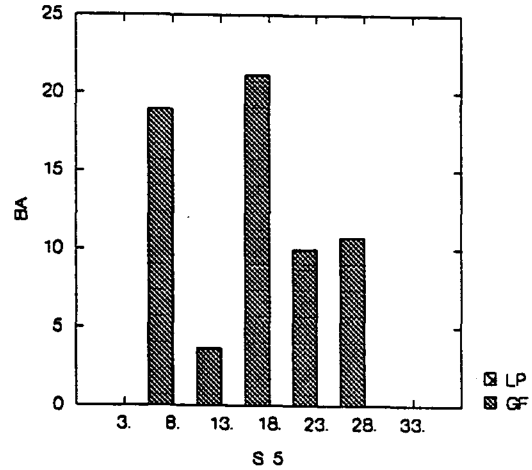
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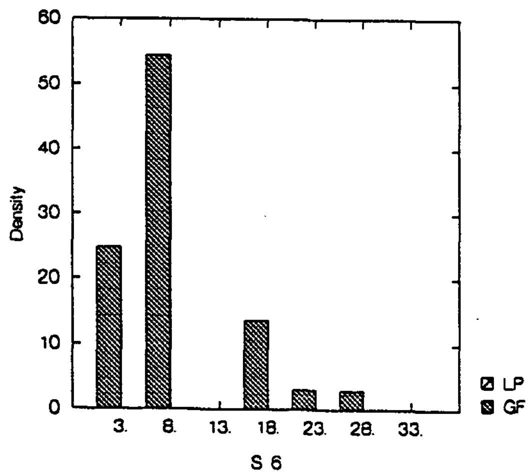
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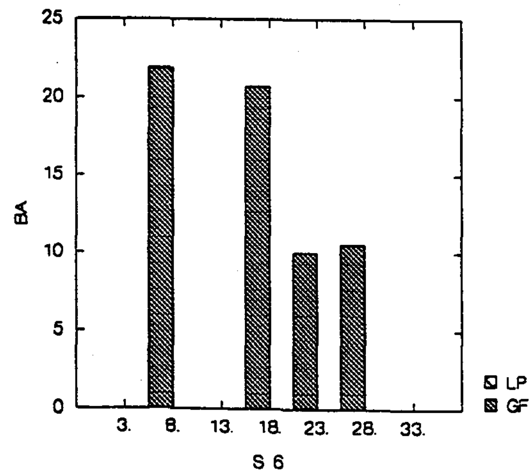
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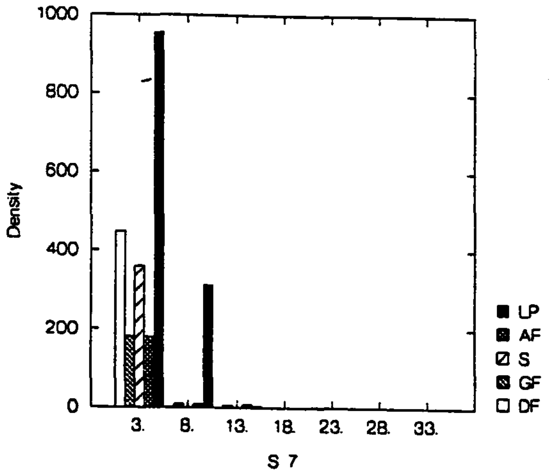
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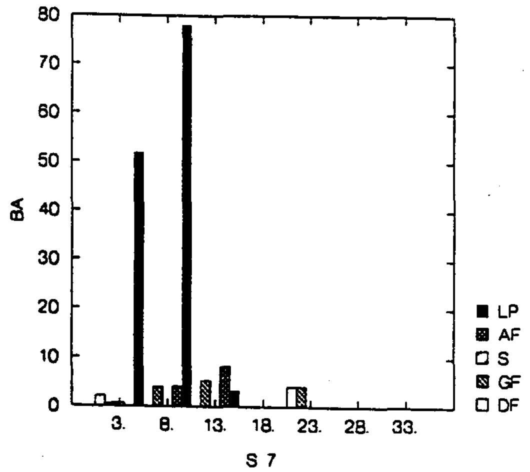
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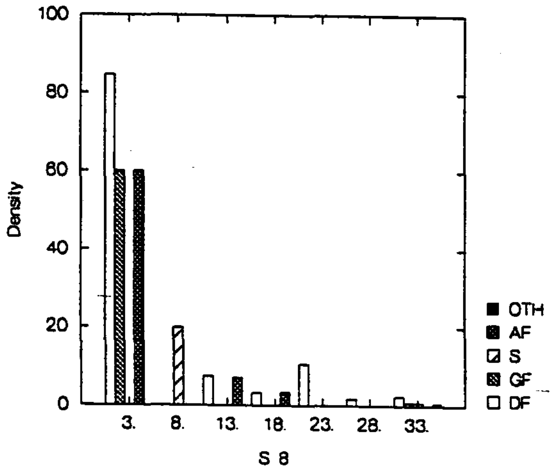
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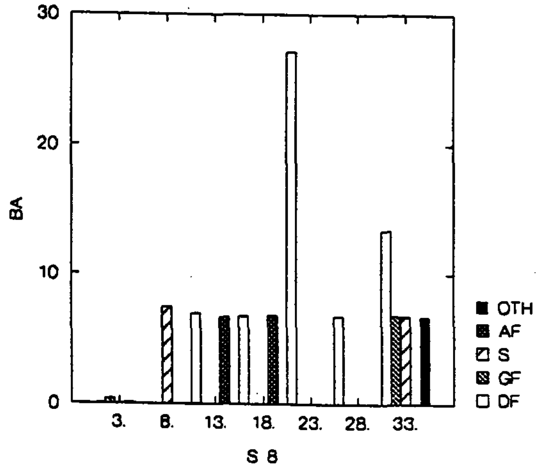
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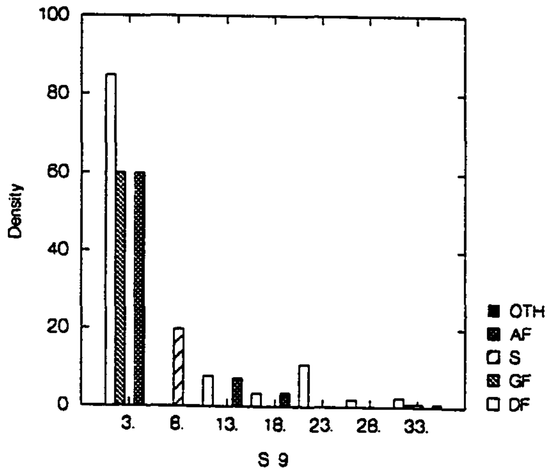
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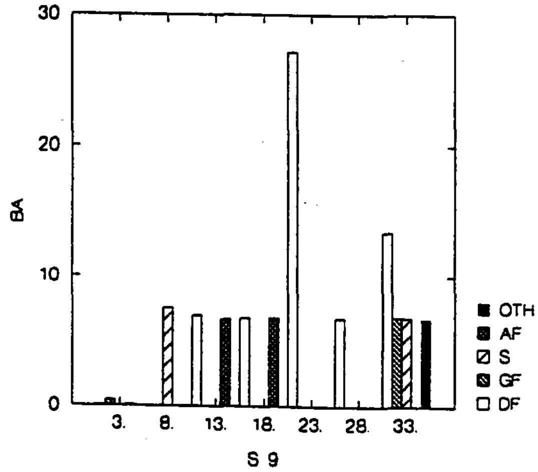
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5.2 Scenario Results: Two Fires

Two fires occurred in five of the nine stands. The fires were set to burn in 2040 and 2140 assuming the following conditions:

- the fire was a normal wild-fire (*i.e.*, the flame length was as calculated by the model).
- moisture conditions were the pre-set "very-dry" case, with temperatures of 90°F.
- wind conditions were the default value of 20 mph at 20 feet. Because of the high canopy closure (as measured by CCF) in most stands, the mid-flame wind speed was 2 mph.

Tables 5.2 and 5.3 are examples of optional model output that summarizes fire conditions and fire impacts. Table 5.2 summarizes user-defined conditions at the time of the burns, and information on the selected fuel model, and the calculated flame length and scorch height. Fire effects are expressed in terms of mineral soil exposure, fuel consumption and smoke production (Table 5.3).

Table 5.2: The conditions present when the fires occurred in 2040 and 2140. Note that only the last three columns are computed by the model (static fuel model, flame length, and scorch height); the other columns are user inputs. Note that the fuel model is set to 0 to indicate that the dynamic fuel models were used.

CONDITIONS AT THE TIME OF THE FIRE

YEAR	STAND ID	% MOISTURE 1 HR	10HR	100H	LIVE	MID FLAME WIND (MPH)	SLOPE (%)	FUEL MODEL	FLAME LNGTH (FT)	POTENTL SCORCH HT (FT)
2040	51201111	3	3	5	69	2.0	30	0	6.9	47.
2040	51201159	3	3	5	69	2.0	30	0	11.0	92.
2040	51201160	3	3	5	69	2.0	30	0	6.3	41.
2040	51203138	3	3	5	69	2.0	30	0	9.5	75.
2040	51204117	3	3	5	69	2.0	0	0	4.4	24.
2140	51201111	3	3	5	69	2.0	30	0	11.0	92.
2140	51201159	3	3	5	69	2.0	30	0	11.0	92.
2140	51201160	3	3	5	69	2.0	30	0	10.6	87.
2140	51203138	3	3	5	69	2.0	30	0	9.7	77.
2140	51204117	3	3	5	69	2.0	0	0	9.5	75.

Table 5.3: The effects of each of the fires. Notice that the second smoke production column (< 10 microns) includes all the smoke less than 2.5 microns that was produced. Total consumption is the total consumption of the individual fuel pools listed here and does not include the consumption of the crowns of live or dead standing trees. Fire type indicates whether this information shows the effects from a stand-level fire (S) or a fuel treatment (T) or both (B).

YEAR	STAND ID	FIRE TYPE	PERCENT MINERAL SOIL EXPOSR	FUELS CONSUMED (TONS/ACRE) LITR	DUFF	0-3"	3"+	3-6"	6-12"	12"+	HERB& SHRUB	CRWNS	TOTAL CONS.	%CONSUME DUFF	%CONSUME 3"+	% TREES WITH CRWNG	SMOKE PRODUCTION (TONS/ACRE) <2.5	SMOKE PRODUCTION (TONS/ACRE) < 10
2040	51201111	S	60	.6	7.9	14.5	7.0	3.7	2.6	.6	.4	3.3	33.5	77	71	80	.28	.33
2040	51201159	S	60	1.4	32.6	32.0	30.3	9.7	14.8	5.7	.2	14.6	111.1	77	61	100	1.04	1.23
2040	51201160	S	60	.8	24.2	13.1	7.6	4.0	3.1	.5	.2	7.9	53.8	77	72	100	.52	.62
2040	51203138	S	60	.9	20.2	19.0	27.8	17.5	9.8	.5	.3	6.4	74.6	77	78	89	.72	.85
2040	51204117	S	60	.7	12.5	10.8	6.3	2.9	2.3	1.1	.3	5.3	35.9	77	65	89	.33	.39
2140	51201111	S	60	1.4	25.9	32.4	37.1	13.4	16.5	7.2	.4	8.1	105.3	77	62	80	.98	1.15
2140	51201159	S	60	1.9	40.5	33.0	44.1	5.9	16.9	21.3	.2	19.7	139.4	77	48	100	1.35	1.59
2140	51201160	S	60	1.9	27.2	30.0	22.3	3.7	8.0	10.5	.2	19.8	101.5	77	49	100	.93	1.10
2140	51203138	S	60	1.3	23.3	15.5	30.0	11.8	14.1	4.1	.3	7.2	77.6	77	65	89	.77	.91
2140	51204117	S	60	1.4	22.4	32.6	30.1	6.6	9.5	14.0	.3	10.8	97.7	77	50	89	.87	1.03

The following pages show the results from the five stands. Notice that each facing pair of pages shows the results for the same stand. Many common patterns can be seen in the different stands, in spite of their different species composition and stocking levels (see Table 5.1). These are:

1. The change in stand characteristics in or just after 2040 and 2140 due to the fire. In most cases, the fire is stand replacing or almost stand replacing. This is seen in the decrease in BA, density (NOTREES), volume (TOTVOL), and foliage, and the increase in QMD and mortality (MORT). QMD increases because fires kill proportionally more small trees than large trees (see the PERCENT mortality graphs on the second page of each set of output). QMD decreases (and the density increases) just after a fire because of the influx of small, newly established trees.

2. The corresponding change in fire model variables due to the fires. Fuels (Debris) are consumed and therefore decrease, while the large number of dead trees is reflected in the peaks in snag density and volume. The potential flame length also often changes just after a fire, first from the consumption of fuels (which generally reduces the flame length) and later from the rapid increase in fuels from the new the break-up of the new dead standing trees (through height loss, falling, and crown loss).

3. Snag numbers and sizes. Stands usually have a fairly high density of small snags (less than 12 inches dbh) and a much lower density of large snags (greater than 12 inches). The large snags, however, represent as much, or more, standing volume.

4. Fuels. The small debris pool (less than 3 inches, LESS3) both before and after both fires. In between the two fires, the pool size decreases as there is less input from small snags and snag crowns. The duff pool generally increases between burns, although in some stands this increase is less than in other stands, and in some stands, the duff pool is a roughly the same level at the time of each of the burns. The large debris pool (greater than 3 inches, PLUS3) is always the largest pool present, at least after the first fire. While it always dramatically increases shortly after a burn (due to the falldown and break-up of snags), its behavior thereafter varies between stands. The litter pool remains relatively constant at a low level.

5. If any trees were remaining after either fire, they were the big trees in the stand. In stands which had less than 100% mortality, the second fire was more severe than the first (see Table 5.2 for flame lengths and scorch heights).

Stand 1: Burn in 2040 & 2140

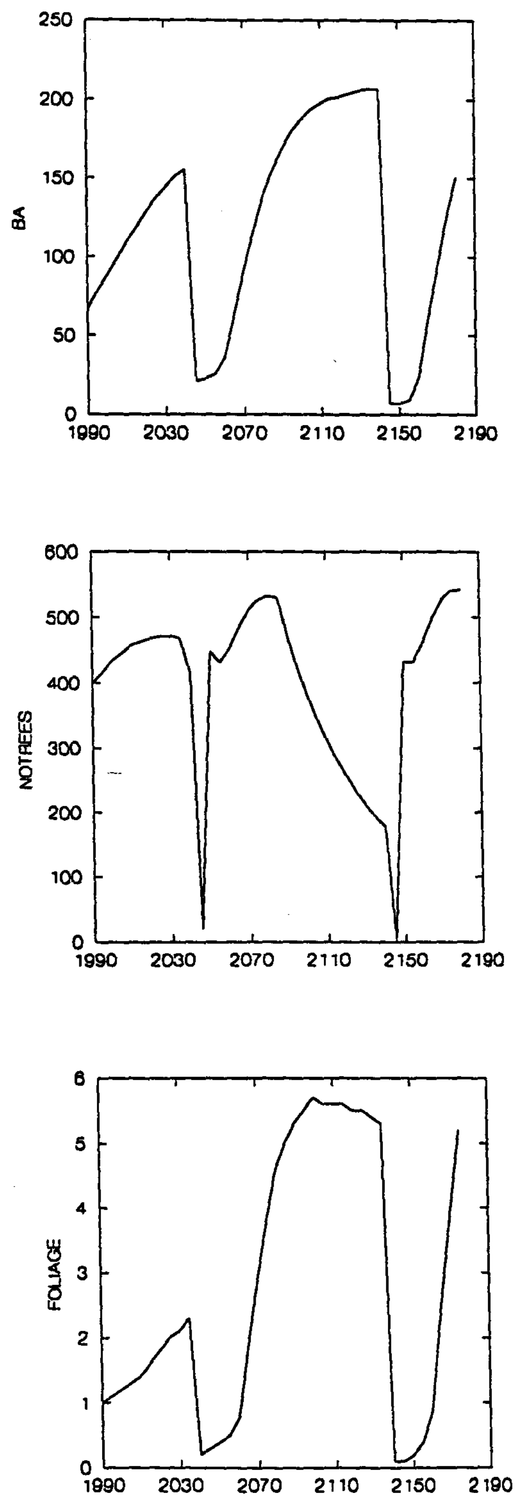
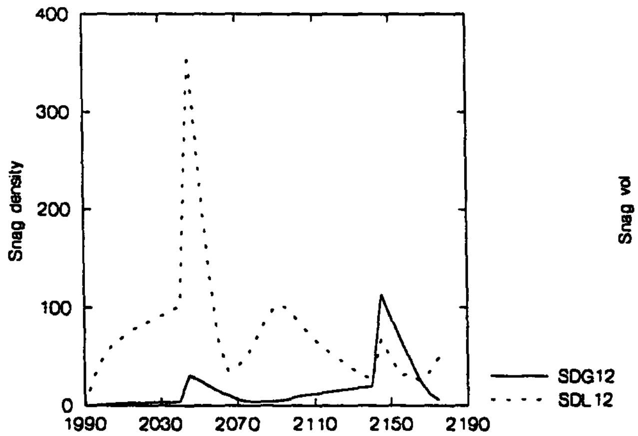
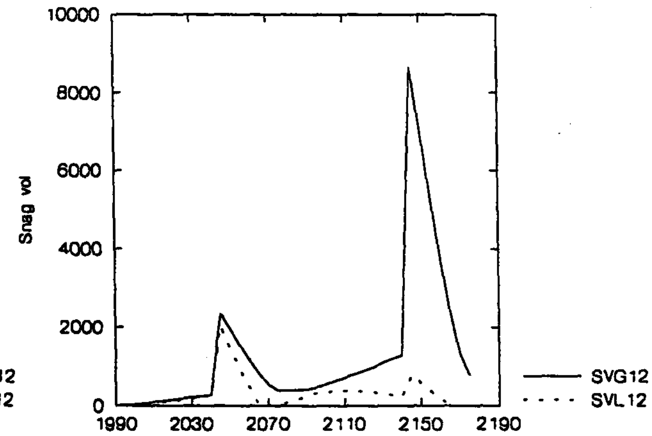
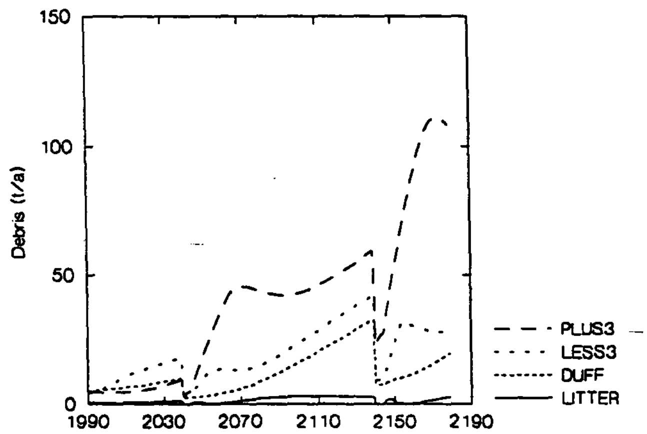


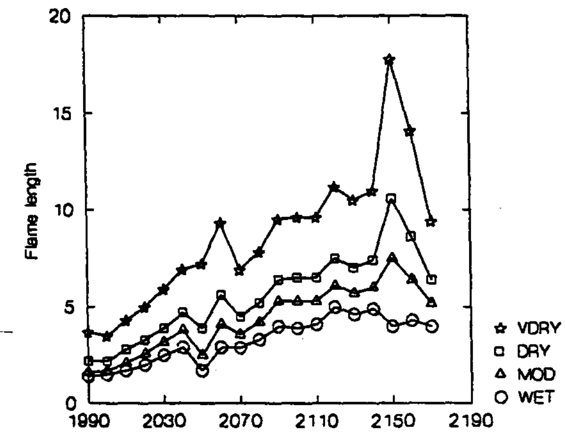
Figure 5.2: Results for the stands with two fires (2040 and 2140). Note that the results for each stand are on facing pages.

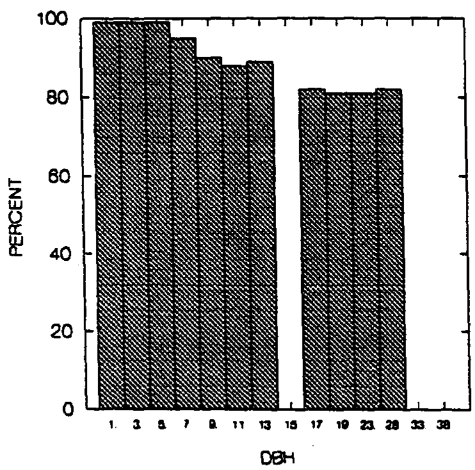
Stand 1: Burn in 2040 and 2140

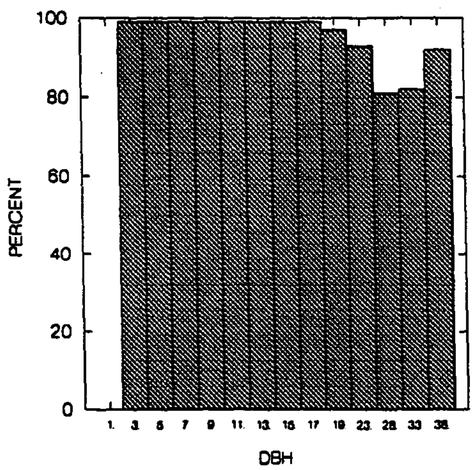




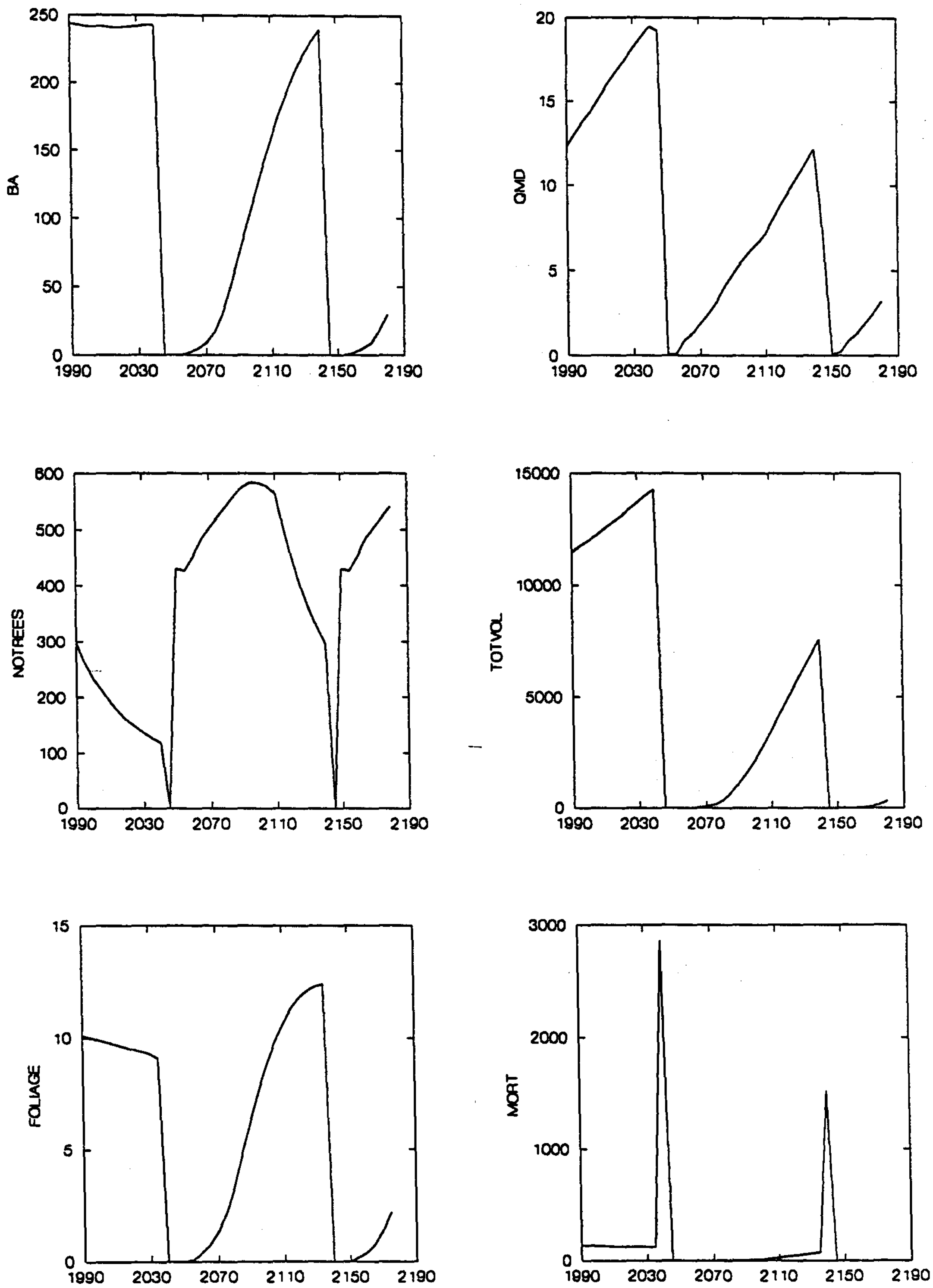




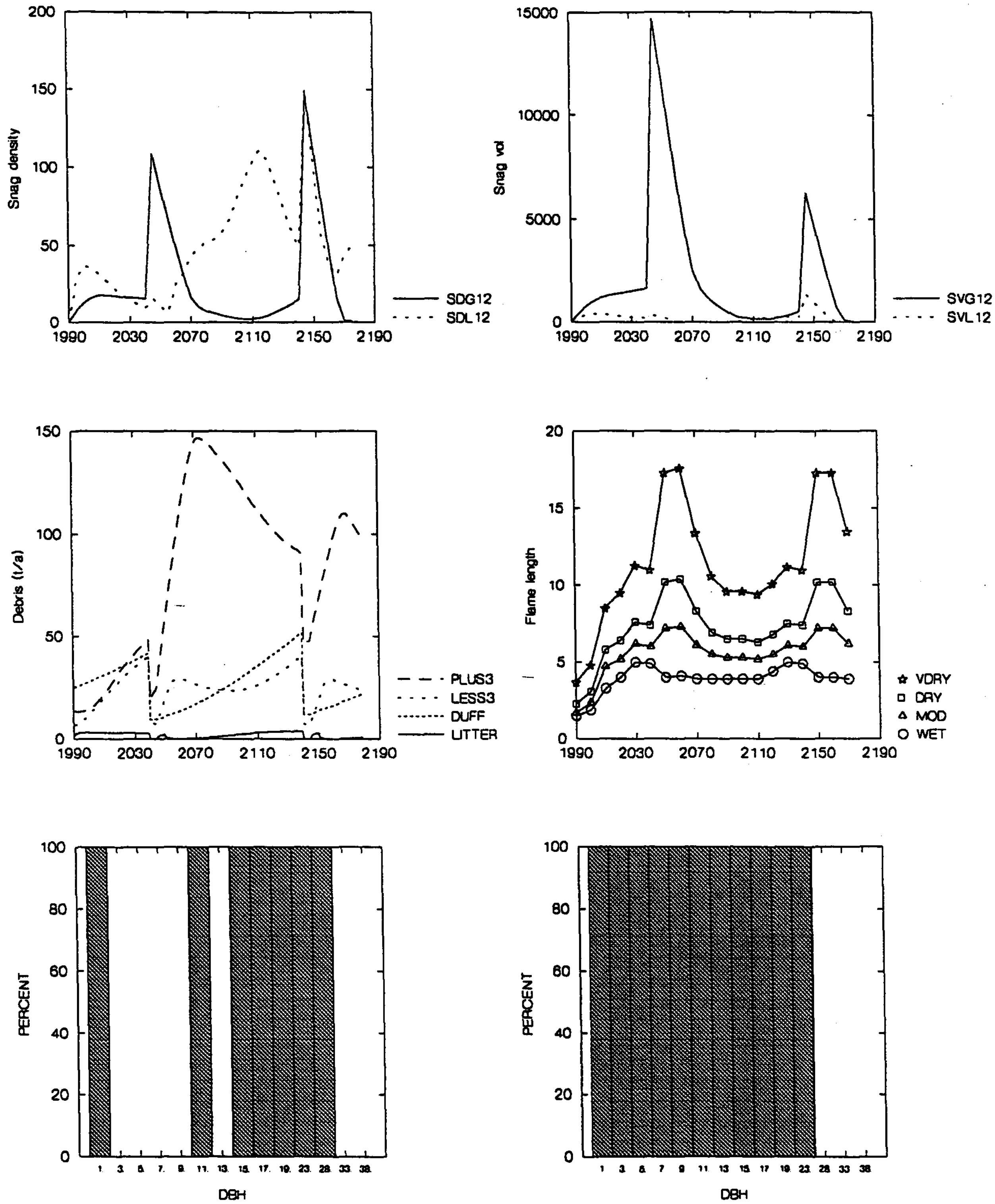




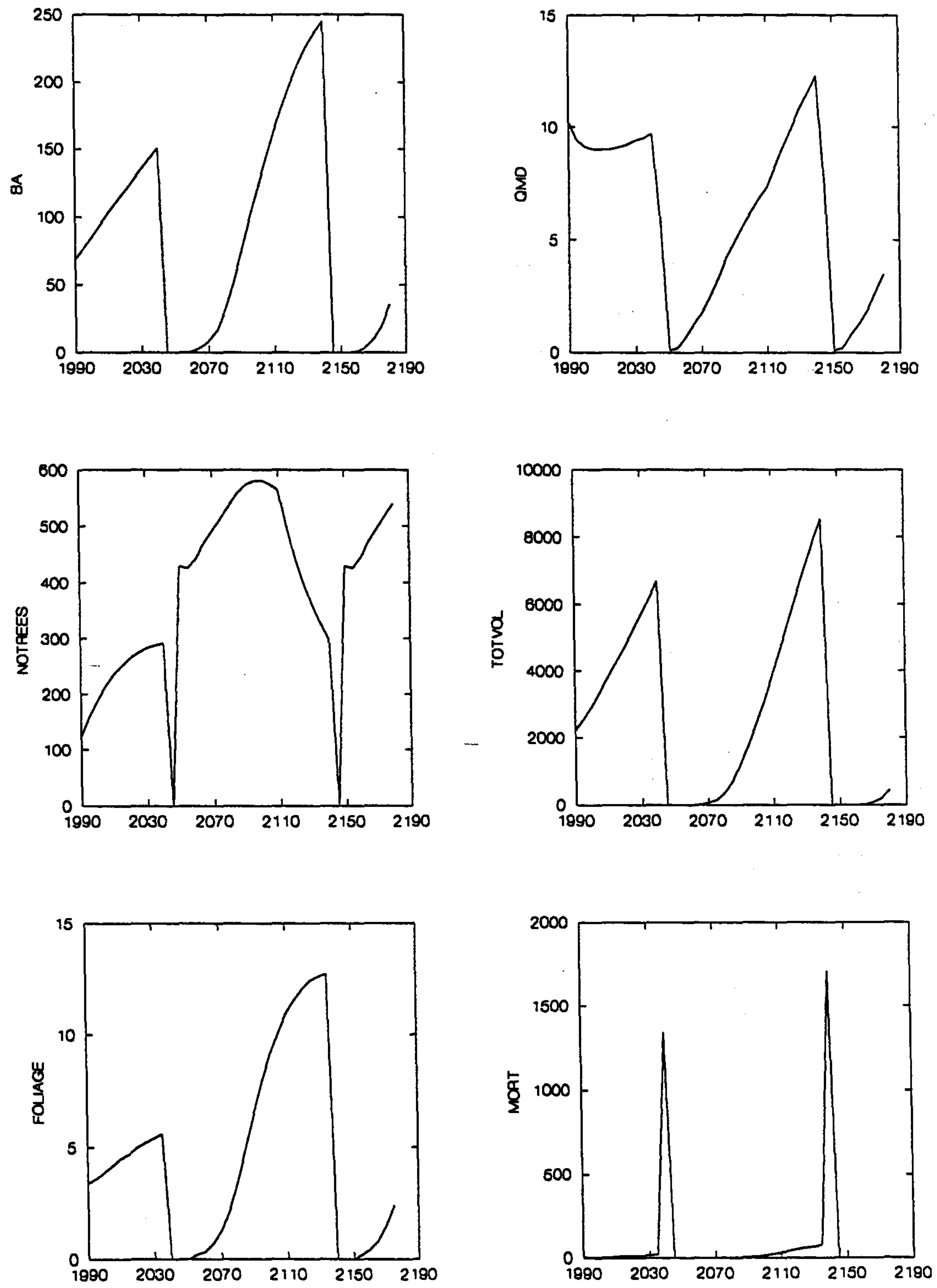
Stand 3: Burn in 2040 and 2140



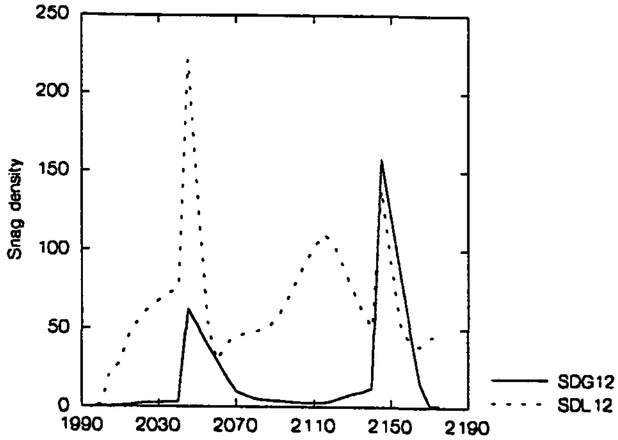
Stand 3: Burn in 2040 and 2140

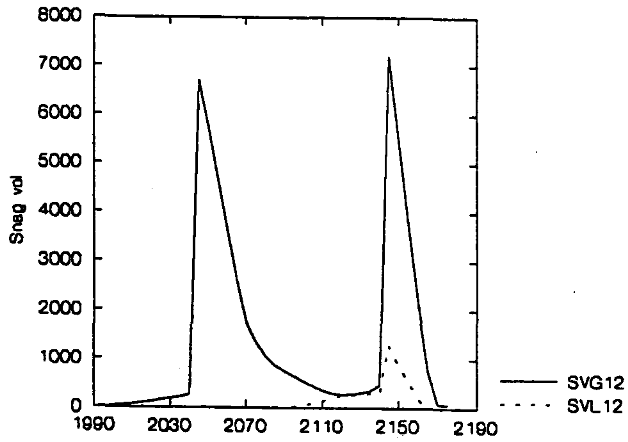


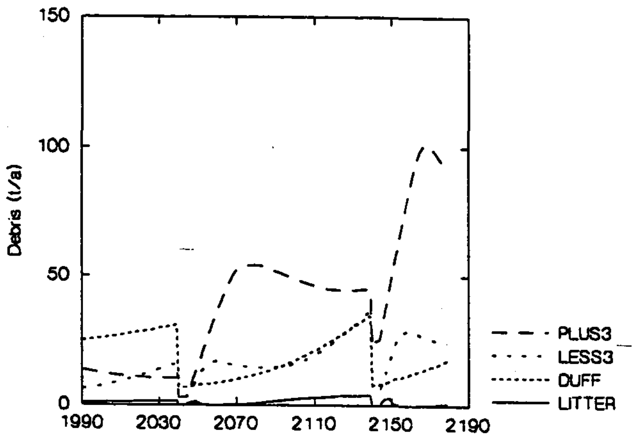
Stand 5: Burn in 2040 and 2140

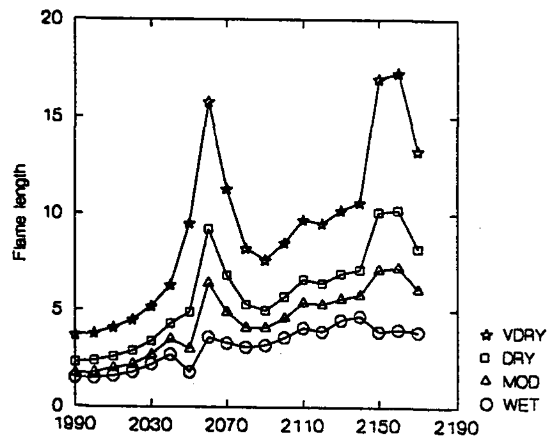


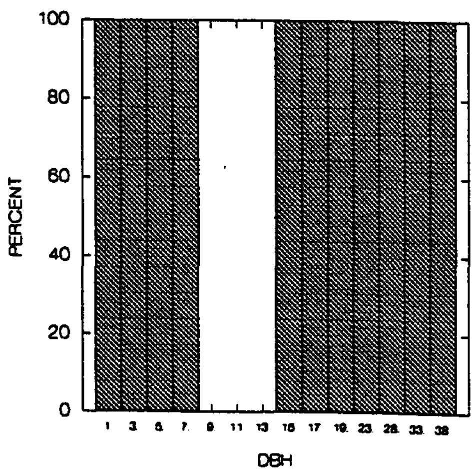
Stand 5: Burn in 2040 and 2140

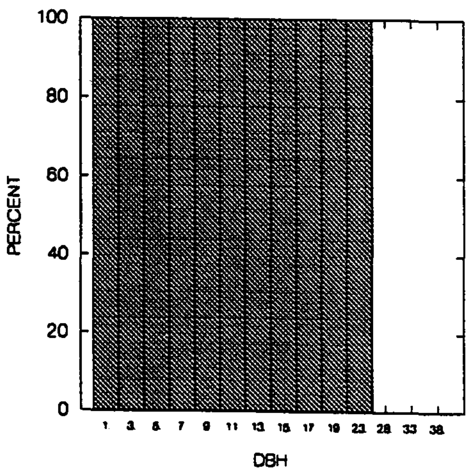




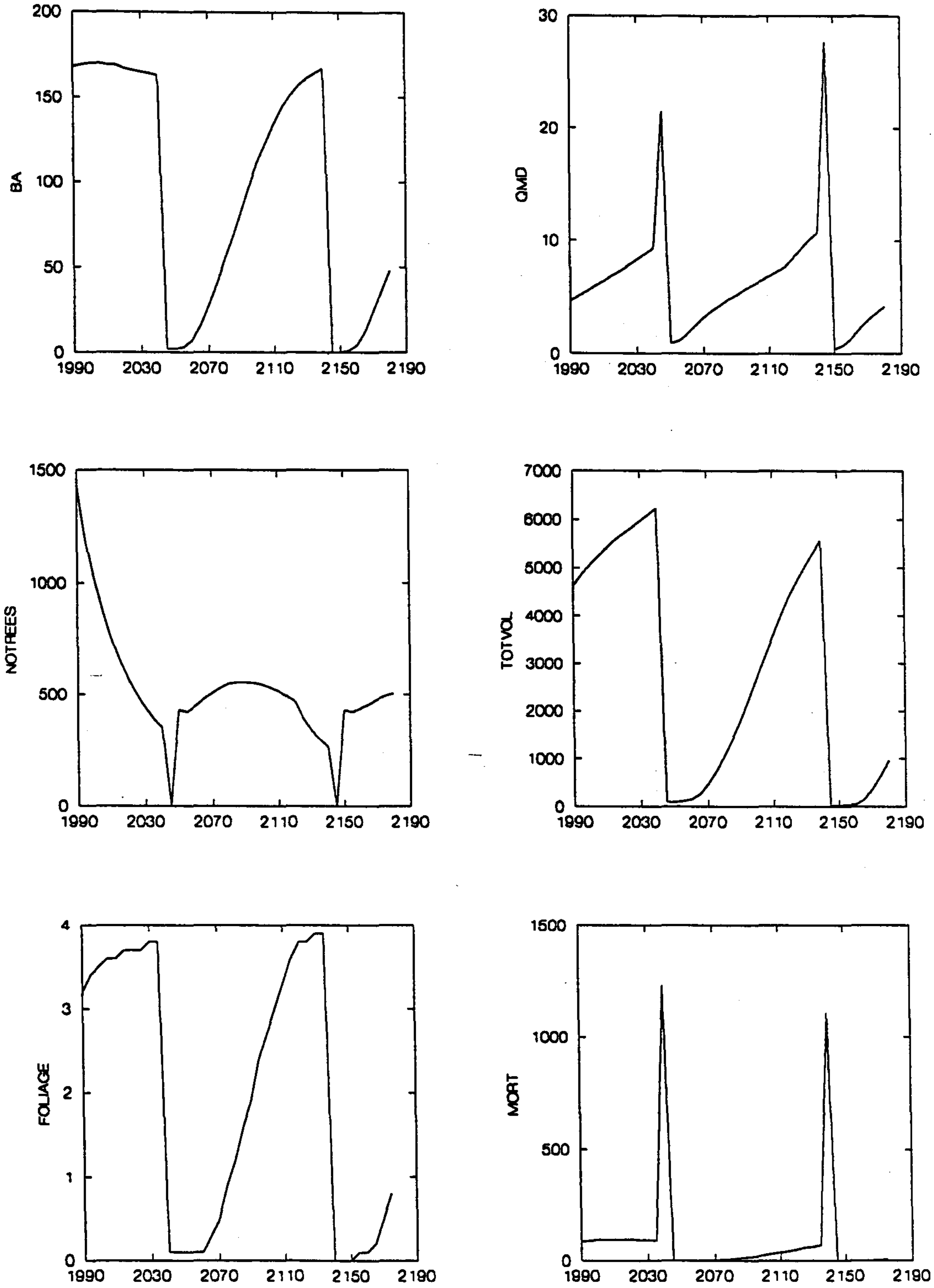




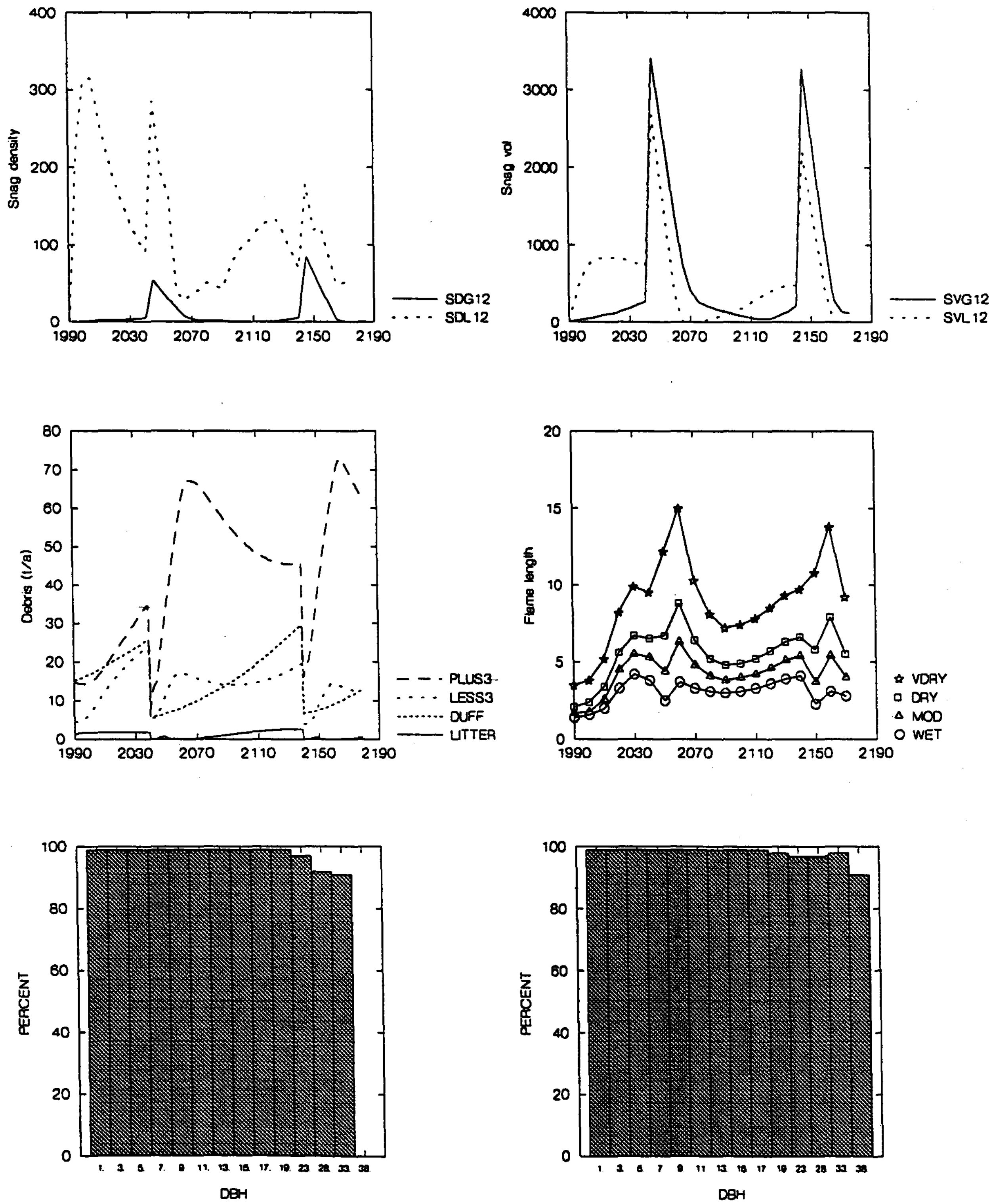




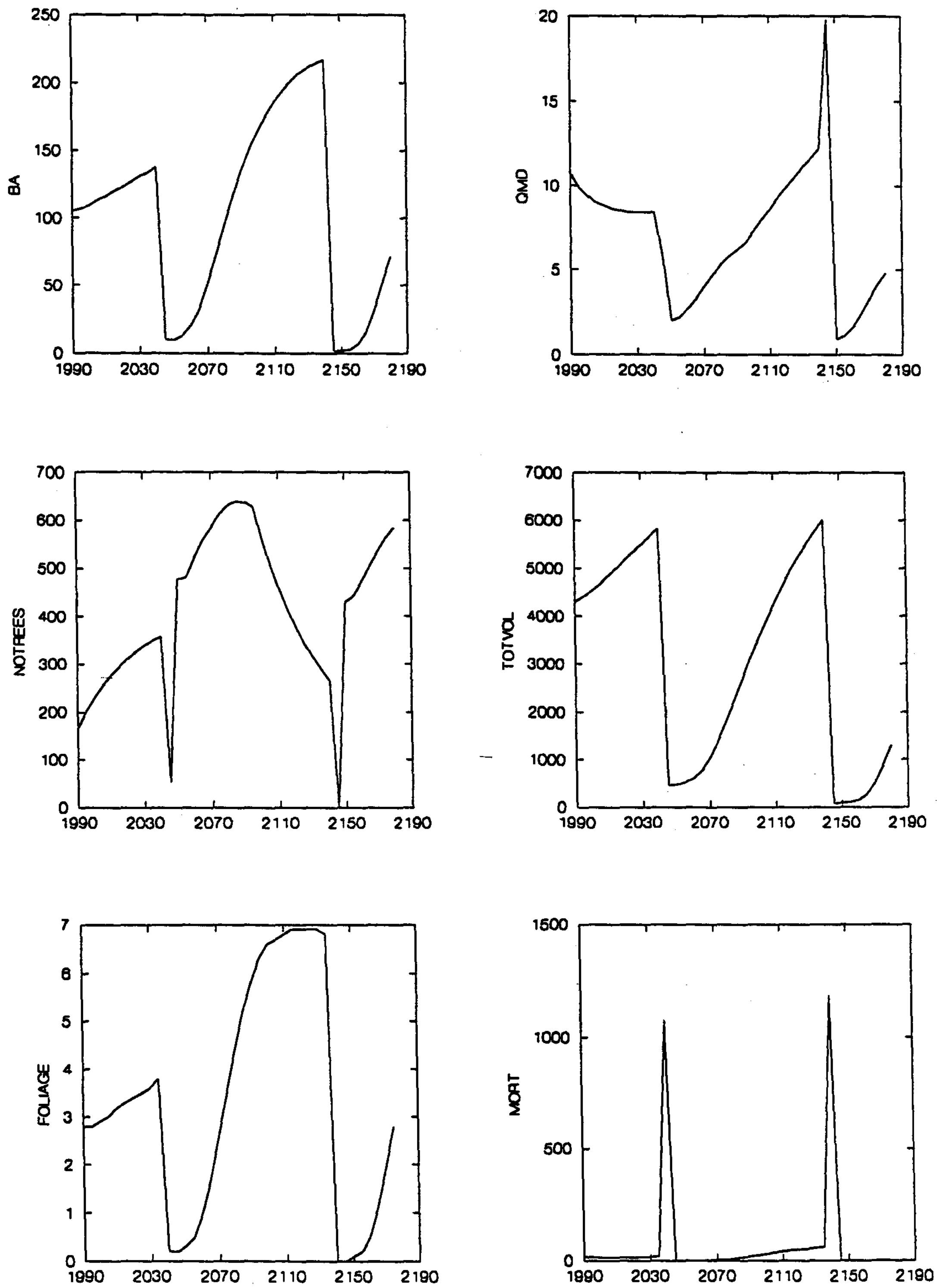
Stand 7: Burn in 2040 and 2140



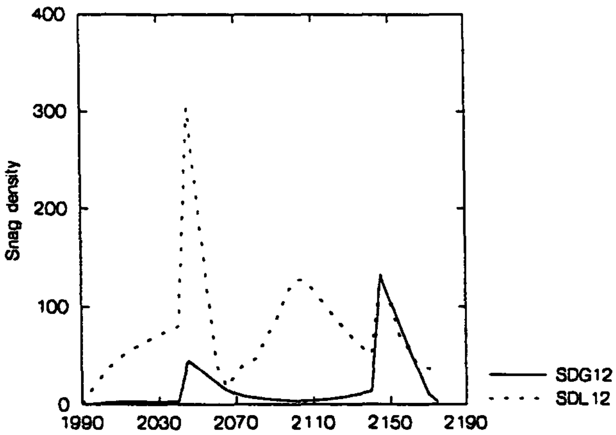
Stand 7: Burn in 2040 and 2140

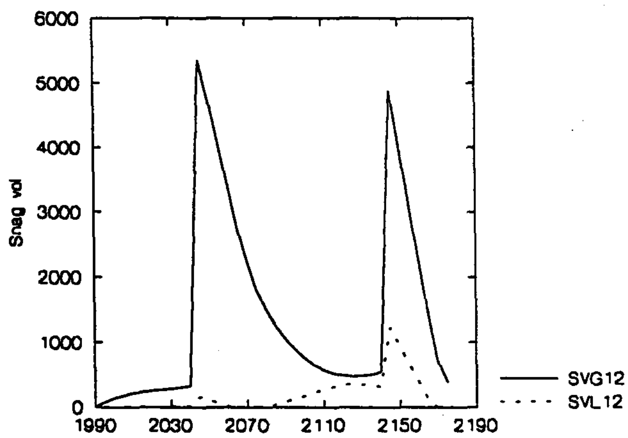


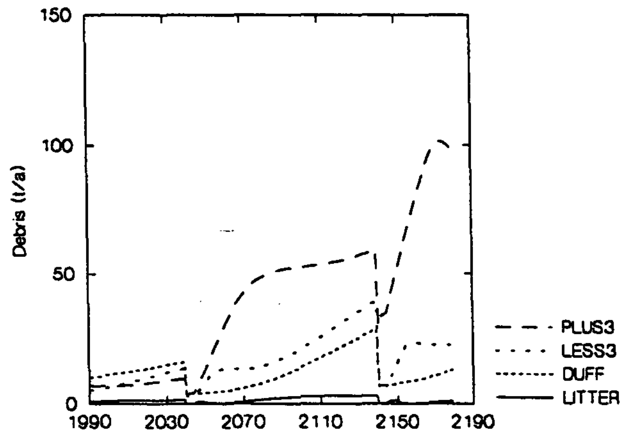
Stand 8: Burn in 2040 and 2140

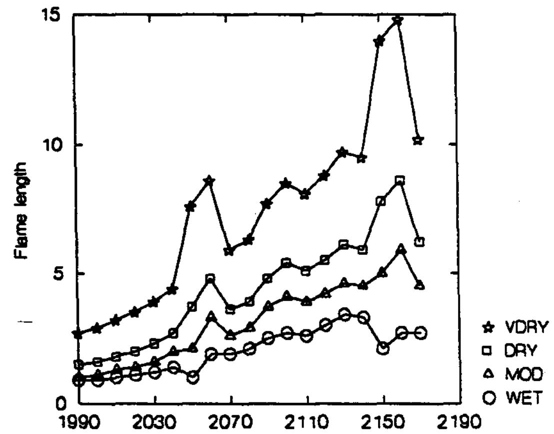


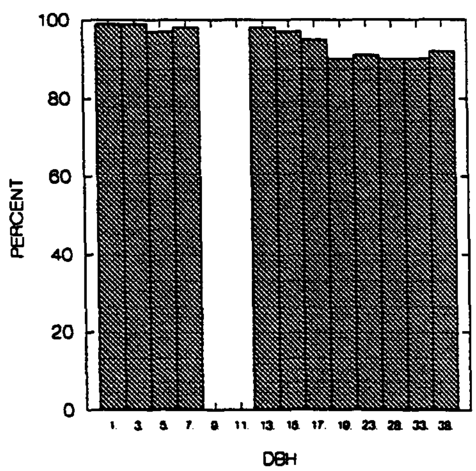
Stand 8: Burn in 2040 and 2140

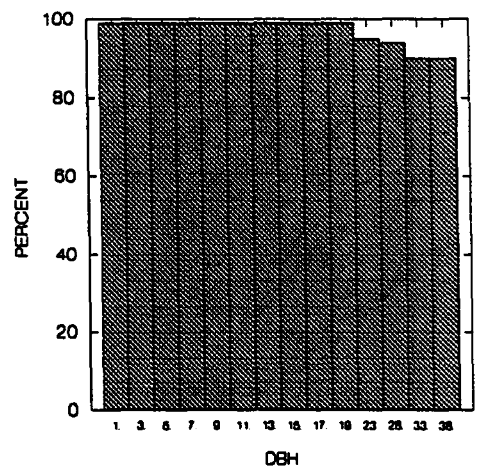












5.3 Scenario Results: One Fire

In order to demonstrate the dynamics of fuels and snags in the absence of regular fires, a single fire occurred in 1995, early in the simulation, in four of the nine stands. The fire in each stand was set assuming the same conditions as in the two-fire scenario:

- the fire was a normal wild-fire (i.e., the flame length was as calculated by the model).
- moisture conditions were the pre-set "very-dry" case, with temperatures of 90°F.
- wind conditions were the default value of 20 mph at 20 feet. Because of the high canopy closure (as measured by CCF) in most stands, the mid-flame wind speed was 2 mph.

The conditions present at the time of the fire (Table 5.4) and fuel consumption and smoke production during the fire (Table 5.5) are optional model output that can be requested by the user.

Table 5.4: The conditions present when the fires occurred in 1995. Note that only the last three columns are variables computed by the model (static fuel model, flame length, and scorch height). The fuel model is set to zero to indicate that the dynamic fuel models were used to select the parameters for the fire intensity model.

CONDITIONS AT THE TIME OF THE FIRE

YEAR	STAND ID	% MOISTURE 1 HR	10HR	100H	LIVE	MID FLAME WIND (MPH)	SLOPE (%)	FUEL MODEL	FLAME LNGTH (FT)	POTENTL SCORCH HT (FT)
1995	51201149	3	3	5	69	2.0	20	0	3.5	17.
1995	51209159	3	3	5	69	2.0	0	0	3.4	16.
1995	51209160	3	3	5	69	2.0	0	0	3.1	14.
1995	51209117	3	3	5	69	2.0	30	0	3.3	15.

Table 5.5: The fuel consumption and smoke production occurring in the 1995 fires. Total consumption is the total consumption of the individual fuel pools listed here and does not include the consumption of the crowns of live or dead standing trees. Fire type indicates whether this information shows the effects from a stand-level fire (S) or a fuel treatment (T) or both (B).

YEAR	STAND ID	FIRE TYP	PERCENT MINERAL SOIL EXPOSR	FUELS CONSUMED (TONS/ACRE) LITR	DUFF	0-3"	3"+	3-6"	6-12"	12"+	HERB& SHRUB	CRWNS	TOTAL CONS.	%CONSUME DUFF	%CONSUME 3"+	% TREES WITH CRWNG	SMOKE PRODUCTION (TONS/ACRE) <2.5	SMOKE PRODUCTION (TONS/ACRE) < 10
1995	51201149	S	60	.7	19.9	5.5	10.4	6.2	4.1	.0	.2	6.8	43.6	77	78	100	.46	.54
1995	51209159	S	60	1.4	20.3	5.9	10.6	6.3	4.2	.0	.2	14.5	52.8	77	78	100	.55	.65
1995	51209160	S	60	.5	19.7	5.3	10.3	6.2	4.1	.0	.2	4.4	40.4	77	78	97	.43	.50
1995	51209117	S	60	.5	8.1	4.3	5.3	3.2	2.1	.0	.3	3.4	22.0	77	78	80	.22	.26

Following are the sets of graphs (as pairs of pages) for each of the four stands. As in the two-fire scenario, differences between stands are predominantly in the numerical values which are seen, not in the general trends.

1. Stand conditions. In all stands, the basal area, volume and QMD increases after the fire while the density decreases. In many cases, foliage biomass decreases towards the end of the simulation period because many of the regression equations for foliage biomass which are used in the fire model asymptotically approach an upper limit. As trees become bigger and fewer, stand foliage biomass decreases.

2. Snags. Small snags (less than 12 inches) again are predominant in their number, although essentially all of the volume of snags is contained in the larger snags (those greater than 12 inches). The number of small snags decreases through the simulation because as they break and fall, they are not replaced by others since most stands contain few, if any small trees later in the simulation.

3. Fuels. Total fuel levels are constantly increasing throughout the simulation period. This increase is seen in all fuel pools except the litter pool. The effect of the snags created by the fire is seen in the increase in the large (PLUS3) and small (LESS3) debris pools just after the fire. Then, as the number of snags drops off dramatically, these pools actually start to decrease in size.

4. Flame lengths. A peak in flame lengths occurs just after the fire, in response to the high levels of large fuels present and the large difference in pool sizes between the small fuels and the large fuels. The flame lengths stabilize in the model at very high total fuel levels due to upper boundary constraints in the equations used in the "dynamic" representation of the static fuel models.

Stand 2: Burn in 1995

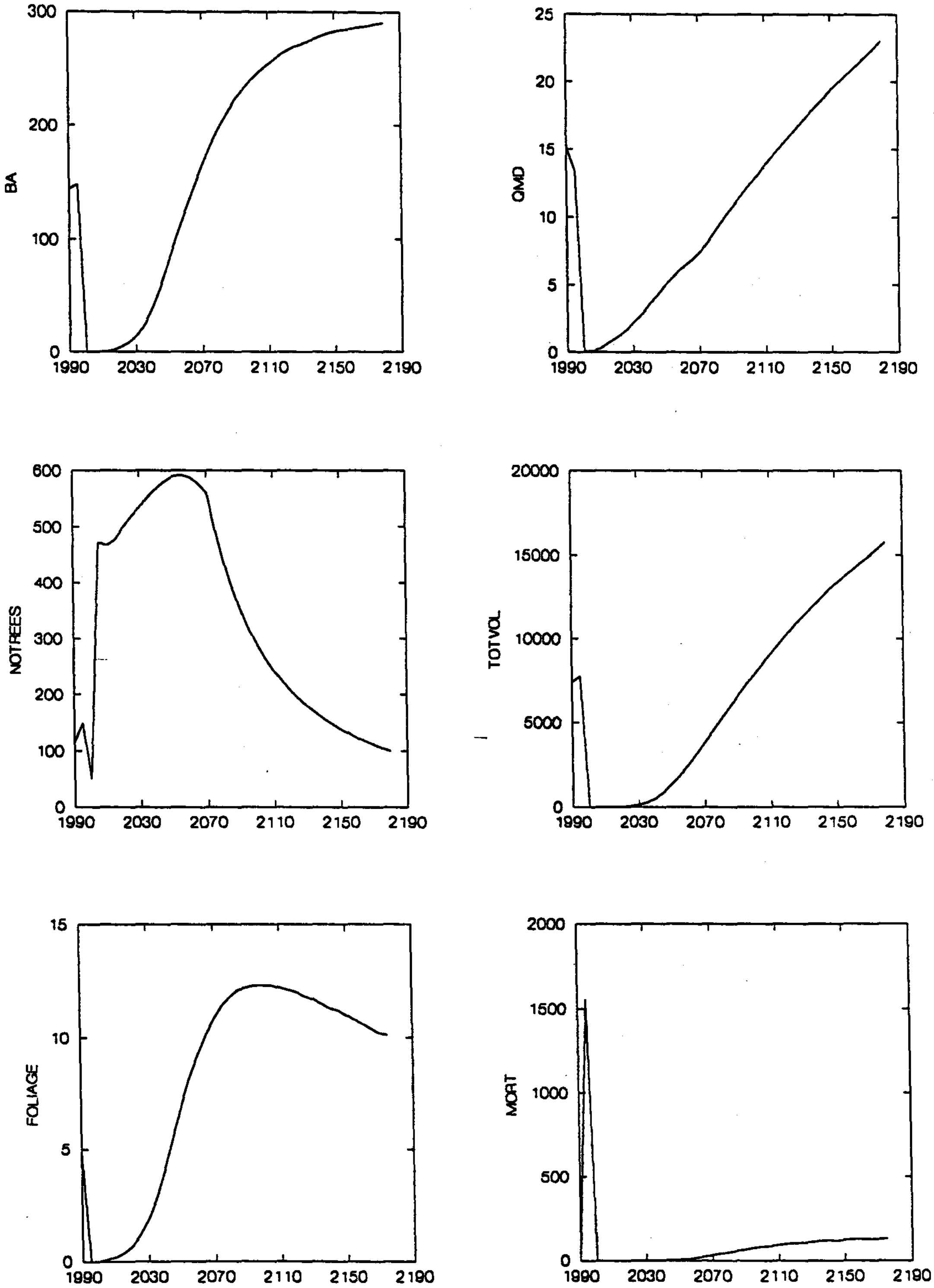
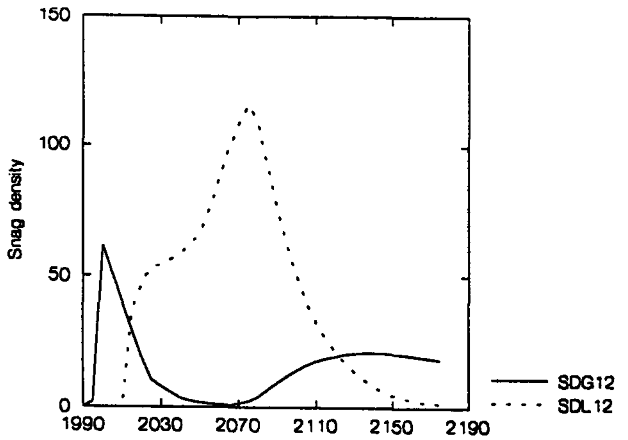
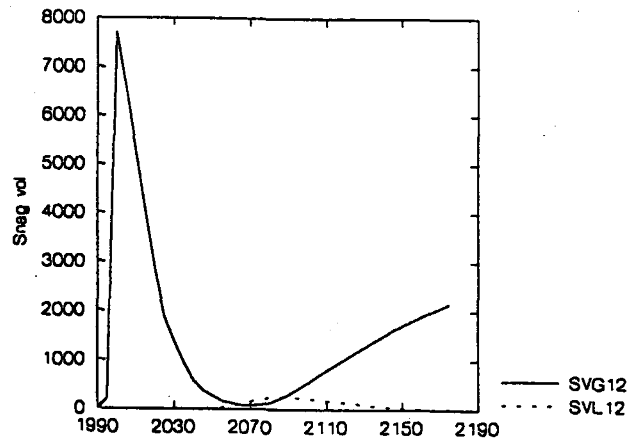
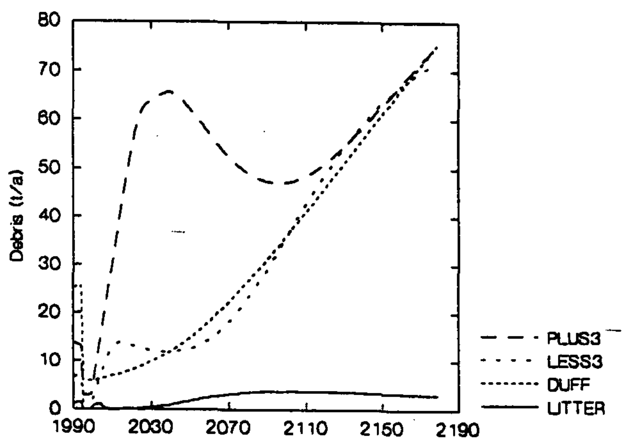


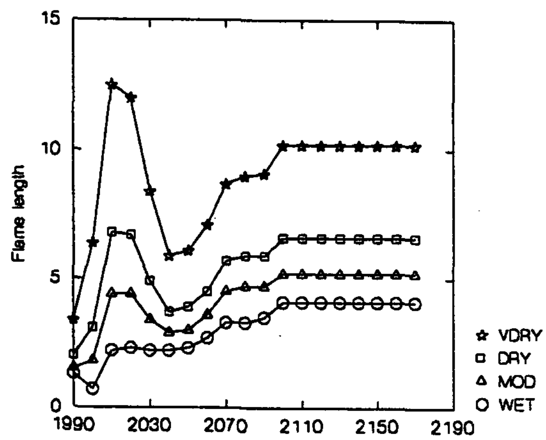
Figure 5.3: Results for the stands with a fire in 1995. Note that the results for each stand are on facing pages.

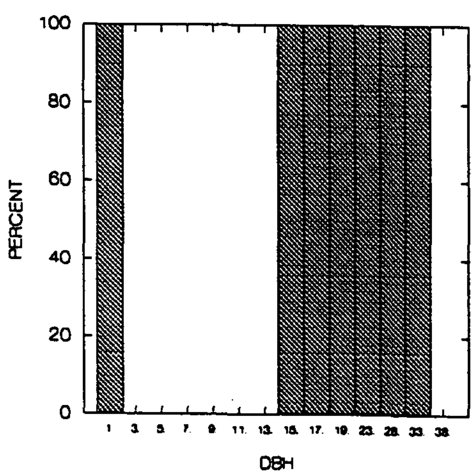
Stand 2: Burn in 1995



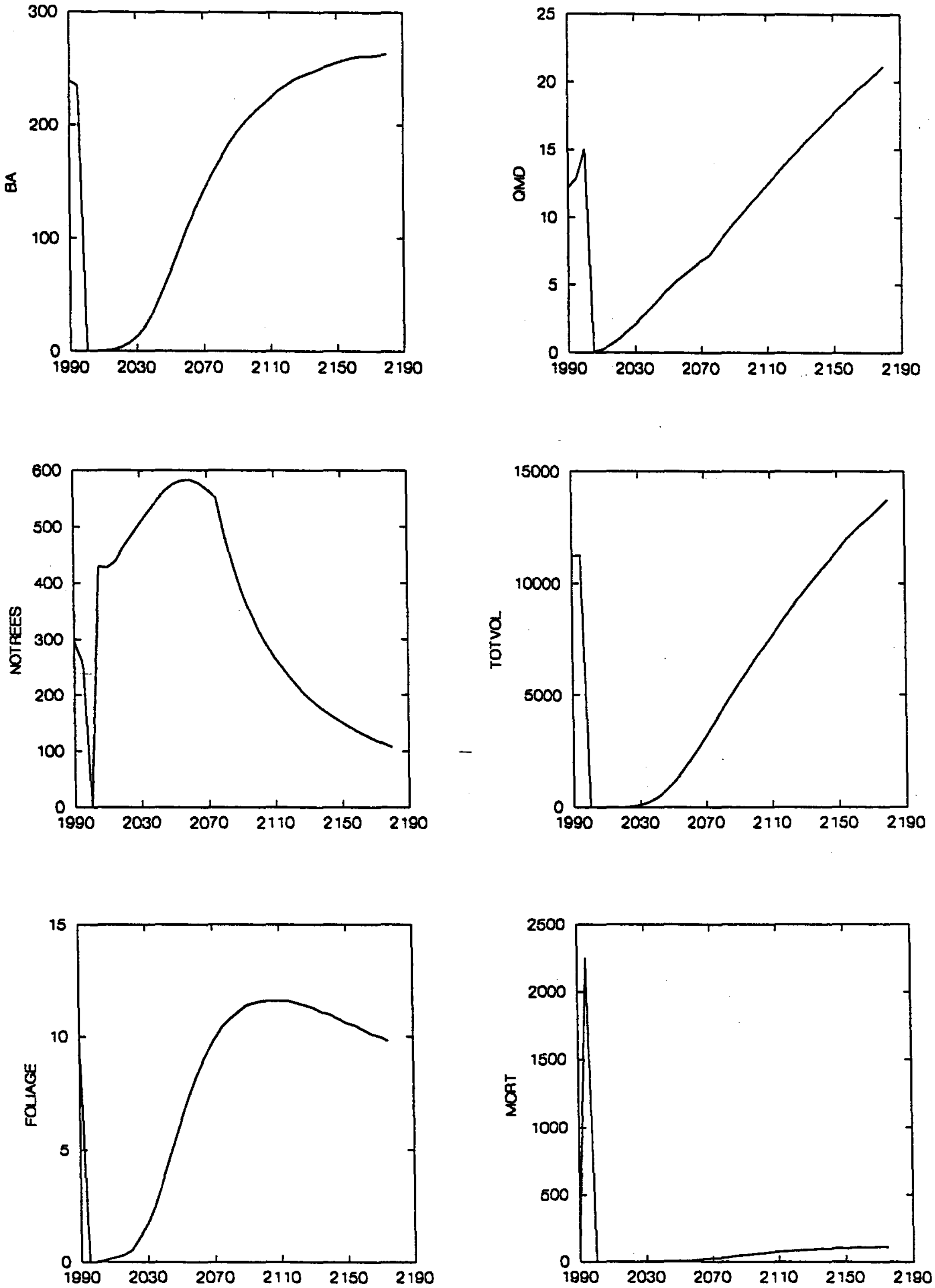




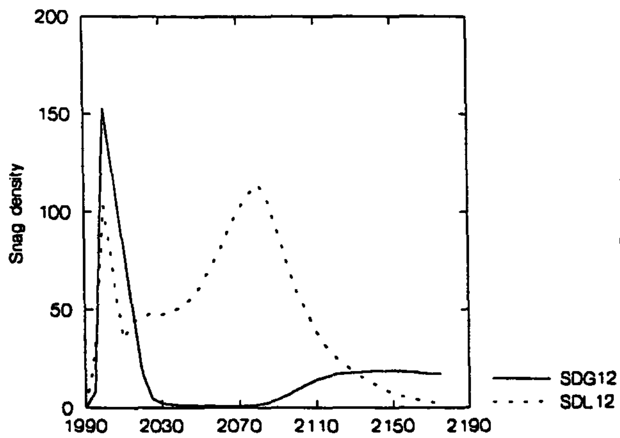


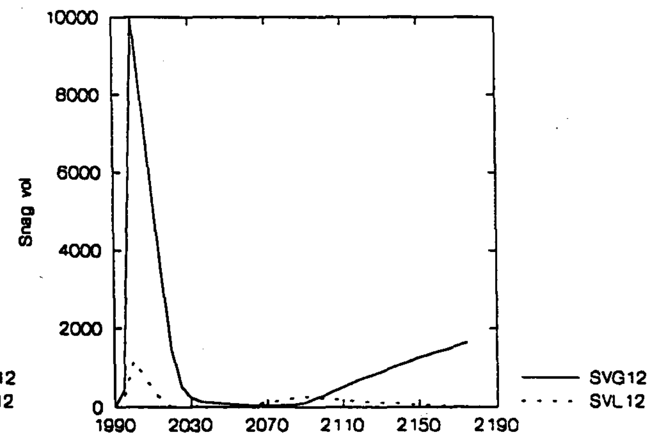


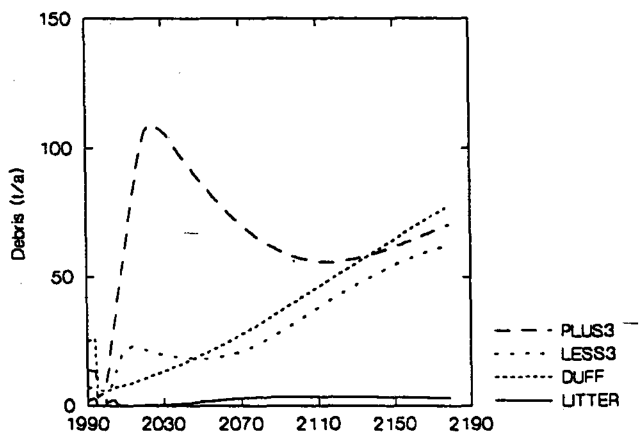
Stand 4: Burn in 1995

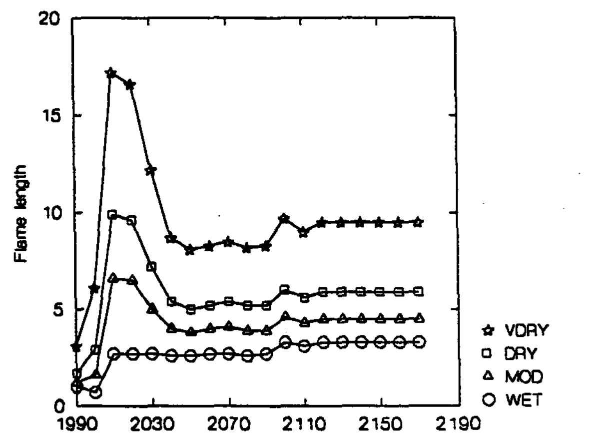


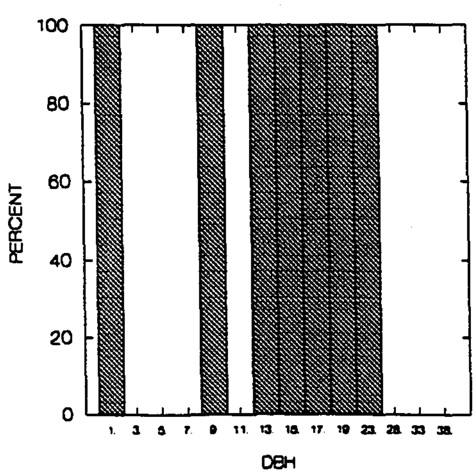
Stand 4: Burn in 1995



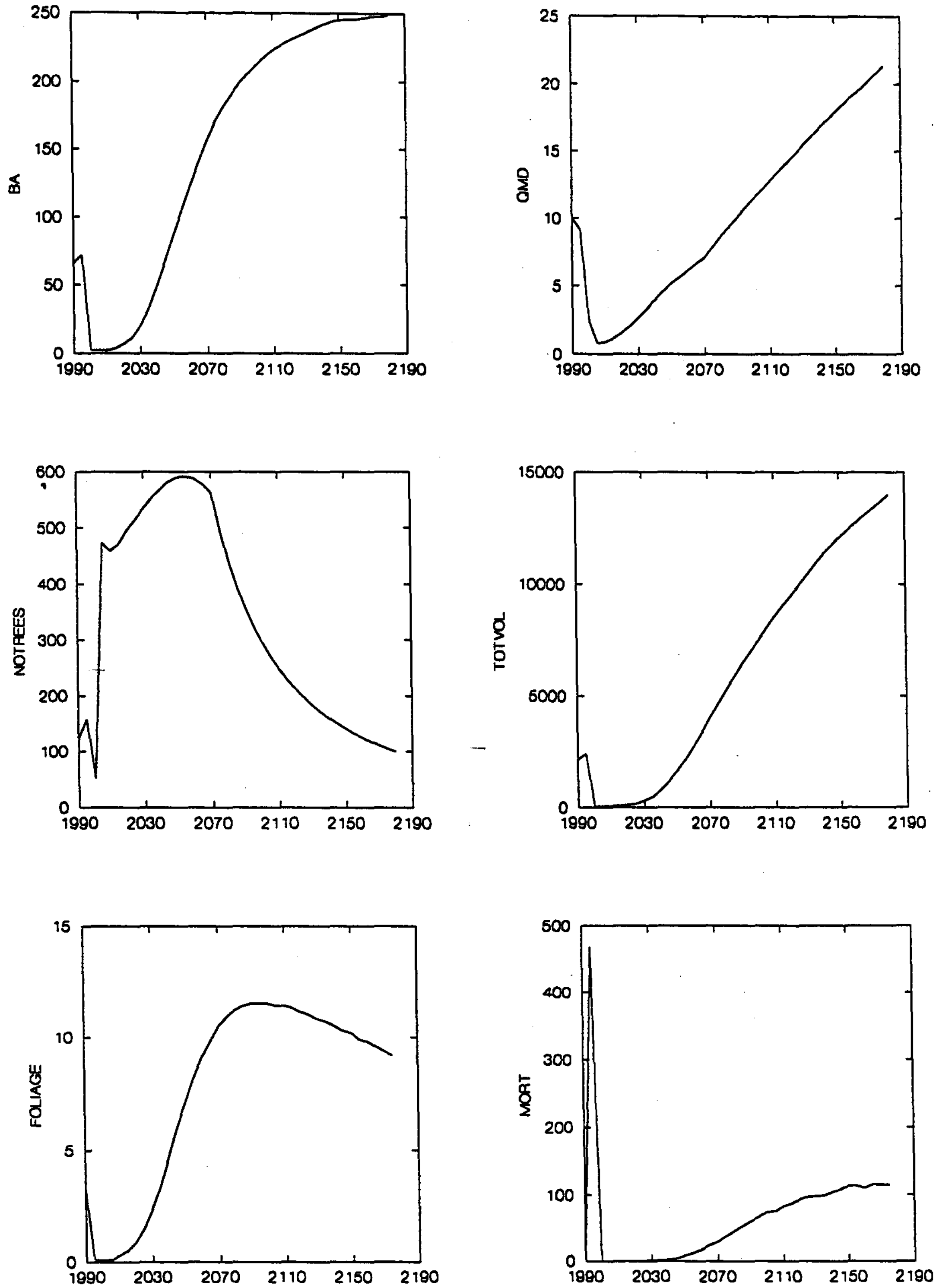




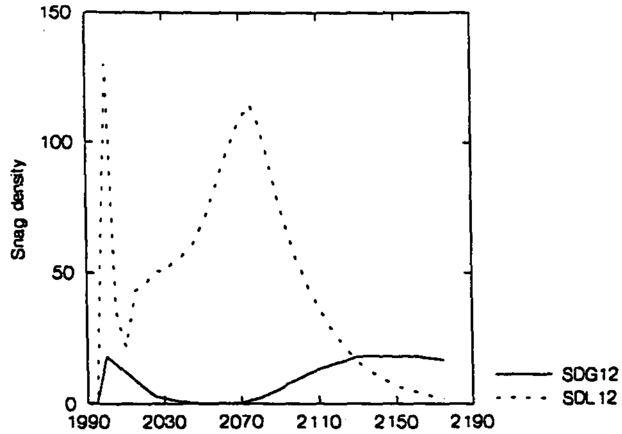


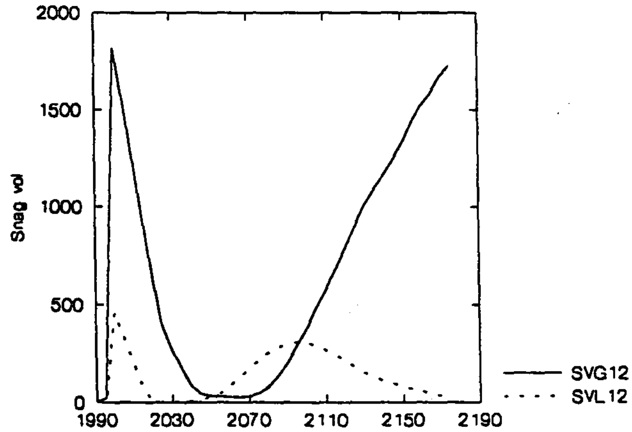


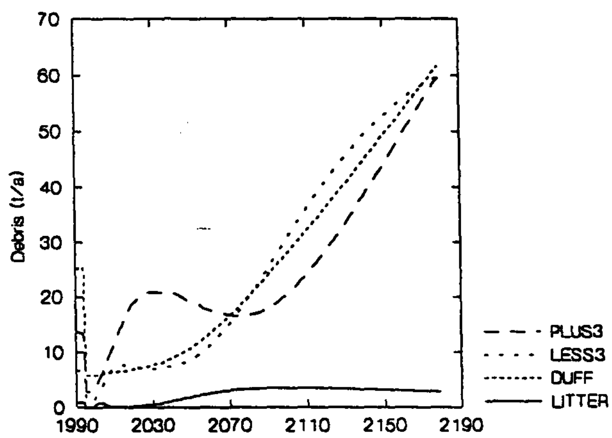
Stand 6: Burn in 1995

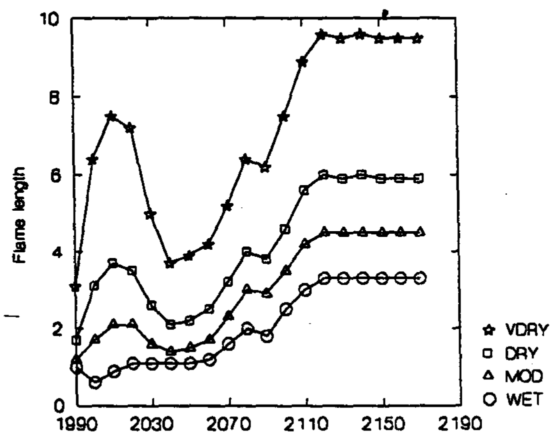


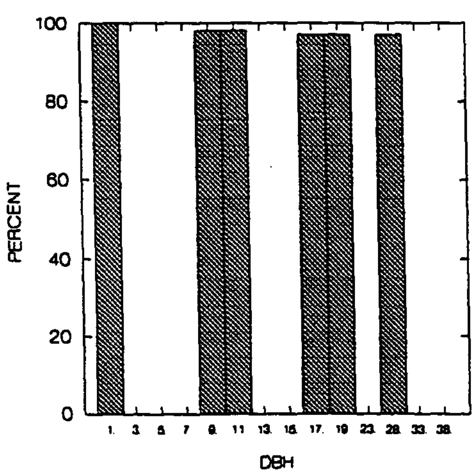
Stand 6: Burn in 1995



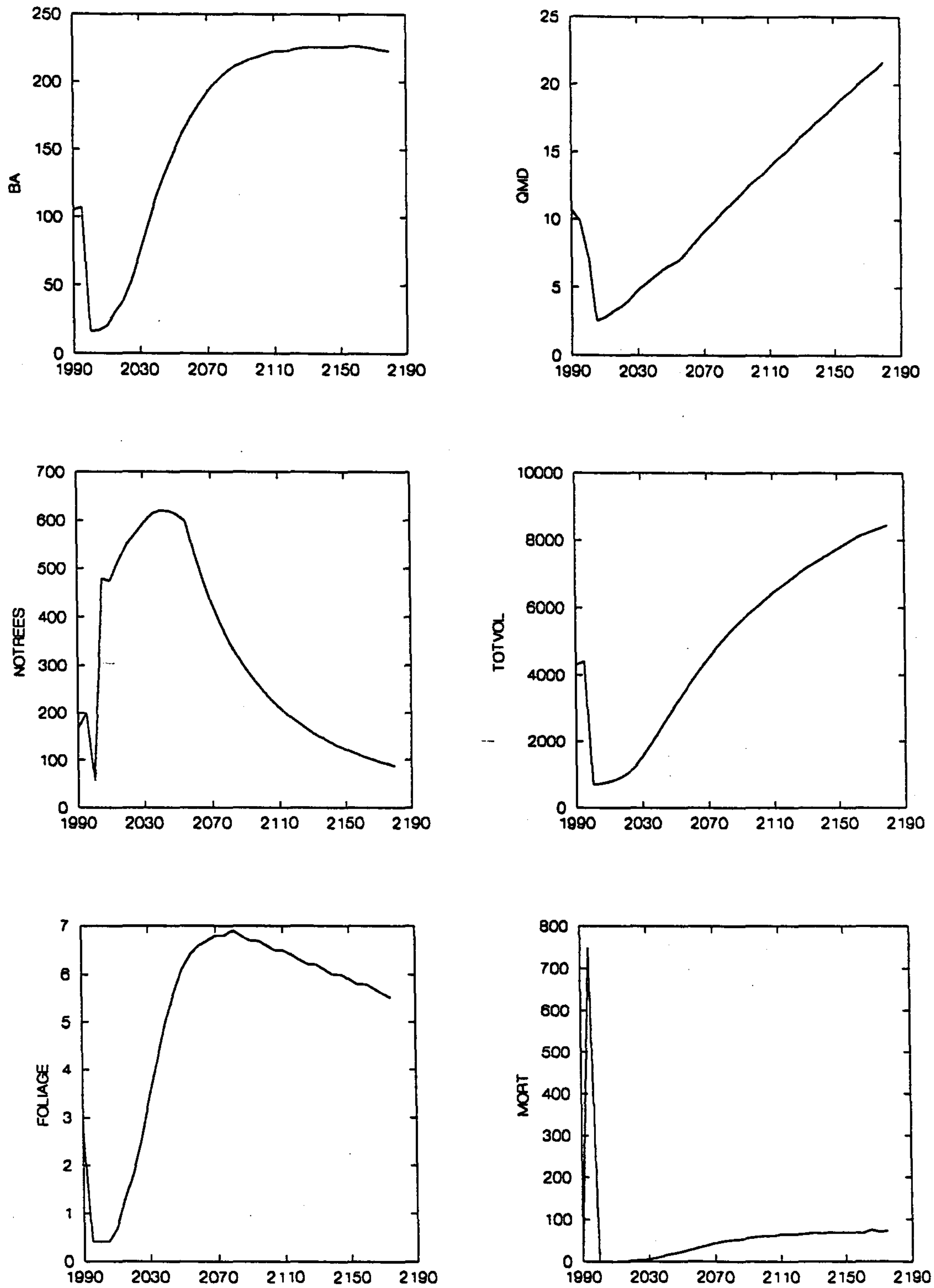




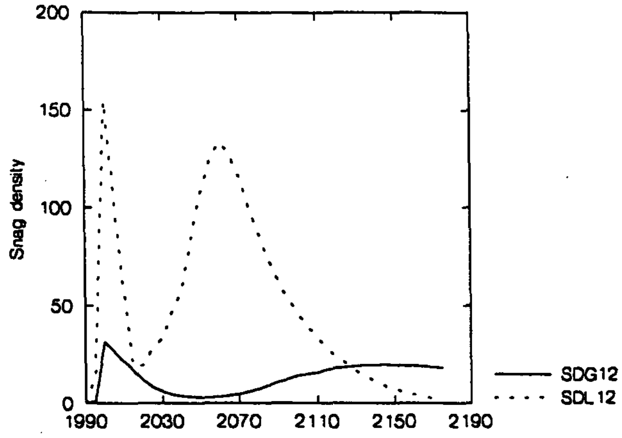


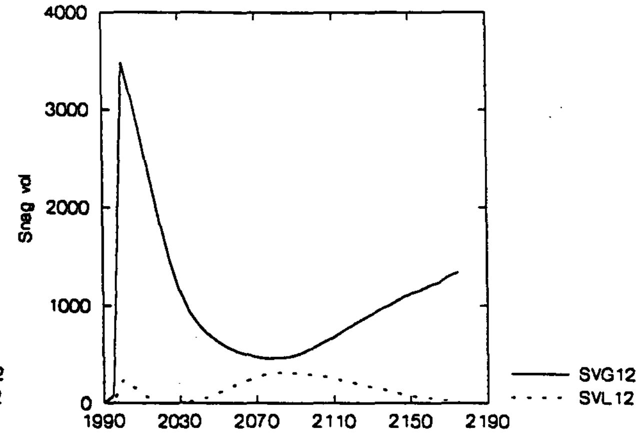


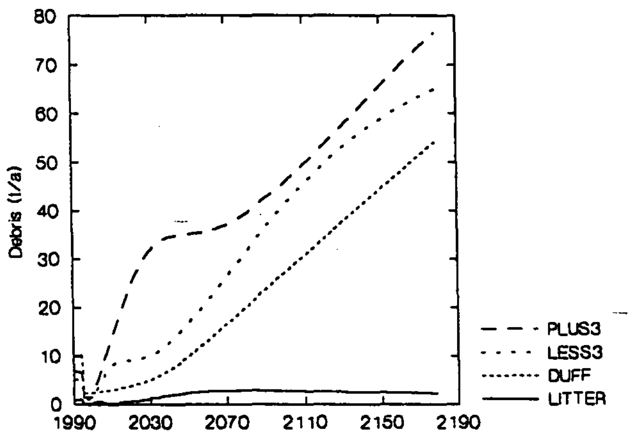
Stand 9: Burn in 1995

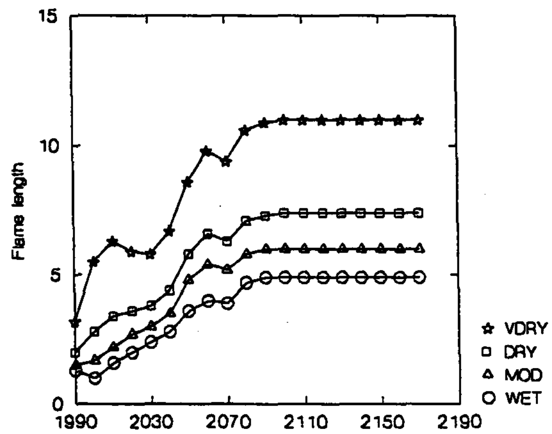


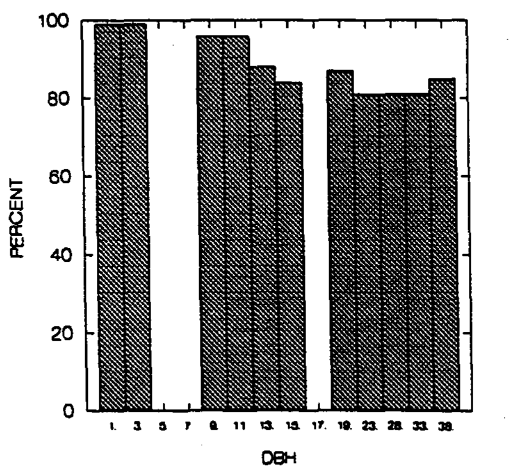
Stand 9: Burn in 1995











5.4 Scenario Results: Landscape Level

The two scenarios were simulated in the same landscape at the same time. This is possible because in the model, the stands have no interaction with each other. During the run, some landscape-level tables were generated which show how the landscape is distributed into different fuel-loading classes or into different static fuel model choices.

As the landscape ages, the fuel loading changes, and is generally increasing in the absence of a fire. The model prints the amount of area in the landscape in five different fuel loading classes: 0-10 tons/acre, 10-20 tons/acre, 20-30 tons/acre and >30 tons/acre, for four different types of fuels: woody fuels less than 3 inches, woody fuels greater than 3 inches, total woody fuels, and snags. Figure 5.4 shows how the area distribution in the landscape changes during the simulation period, in terms of the different fuel loadings categories. The woody fuels and the duff categories clearly show the increase in area with low amounts of fuel when stands in the landscape are burned (1995, 2040, and 2041). In many cases, especially in the case of duff, the landscape is divided into two categories: a low and high fuel loading. This is the result of fires burning some of the stands. Those that burned have low fuel levels while those that did not burn have higher levels. The amount of snags in the landscape, as measured in tons/acre, shows many sharp peaks. This occurs because snags are added to the snag list only once every FVS cycle (every five years) while the snags that are already present are decayed (height is lost and some fall) each year. The decay process reduces the tons/acre of snags that are present. The peaks and valleys occur if one or more stands are close to the boundary for the loading classes, and if these stands cross the boundary with each new snag addition and with the decaying process.

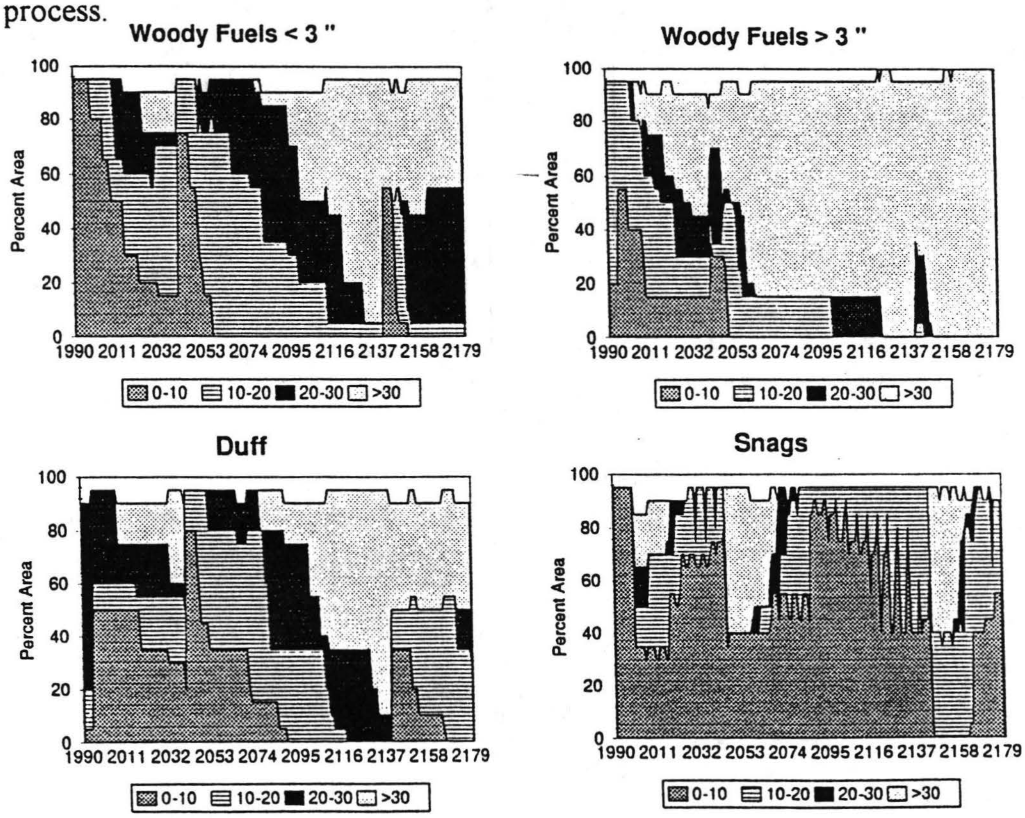


Figure 5.4: Percent of the landscape in different fuel categories. The legend indicates the different loading categories and represents the different amounts of fuel in the stand as measured in tons per acre. This figure was generated from one of the landscape-level output tables.

5.4 Scenario Results: Landscape Level

The two scenarios were simulated in the same landscape at the same time. This is possible because in the model, the stands have no interaction with each other. During the run, some landscape-level tables were generated which show how the landscape is distributed into different fuel-loading classes or into different static fuel model choices.

As the landscape ages, the fuel loading changes, and is generally increasing in the absence of a fire. The model prints the amount of area in the landscape in five different fuel loading classes: 0-10 tons/acre, 10-20 tons/acre, 20-30 tons/acre and >30 tons/acre, for four different types of fuels: woody fuels less than 3 inches, woody fuels greater than 3 inches, total woody fuels, and snags. Figure 5.4 shows how the area distribution in the landscape changes during the simulation period, in terms of the different fuel loadings categories. The woody fuels and the duff categories clearly show the increase in area with low amounts of fuel when stands in the landscape are burned (1995, 2040, and 2041). In many cases, especially in the case of duff, the landscape is divided into two categories: a low and high fuel loading. This is the result of fires burning some of the stands. Those that burned have low fuel levels while those that did not burn have higher levels. The amount of snags in the landscape, as measured in tons/acre, shows many sharp peaks. This occurs because snags are added to the snag list only once every FVS cycle (every five years) while the snags that are already present are decayed (height is lost and some fall) each year. The decay process reduces the tons/acre of snags that are present. The peaks and valleys occur if one or more stands are close to the boundary for the loading classes, and if these stands cross the boundary with each new snag addition and with the decaying process.

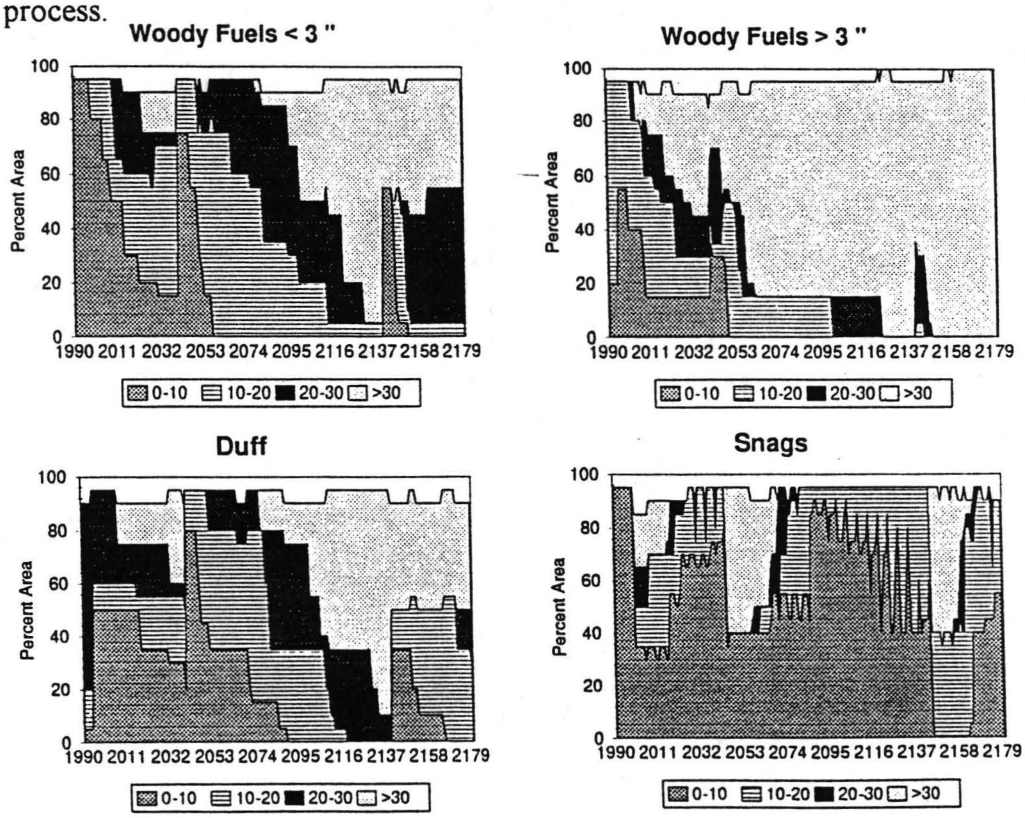


Figure 5.4: Percent of the landscape in different fuel categories. The legend indicates the different loading categories and represents the different amounts of fuel in the stand as measured in tons per acre. This figure was generated from one of the landscape-level output tables.

Many users may be interested in the amount of the landscape that is at risk to fires, or that could experience high fires. Two of the landscape-level output files provide information about the possible severity of fires. In these output files, users can see the percent of the area that is in different static fuel model groups (even if the model is actually using the dynamic representation of the static fuel models), or the percent of the area that would produce flames of different lengths. These can be graphed in the same manner as for the fuels (Figure 5.4). The area in different fuel models is shown in Figure 5.5, and the area producing flames of different lengths is shown in Figure 5.6. Both figures clearly show the effect of the fire. In the first, the fuel model decreases at the time of the fire (Figure 5.5), and in the second, the flame lengths become shorter just after the fire (Figure 5.6). Both changes occur because fuels are consumed: smaller fuel pools lead to a different fuel model being chosen and lead to lower flame lengths.

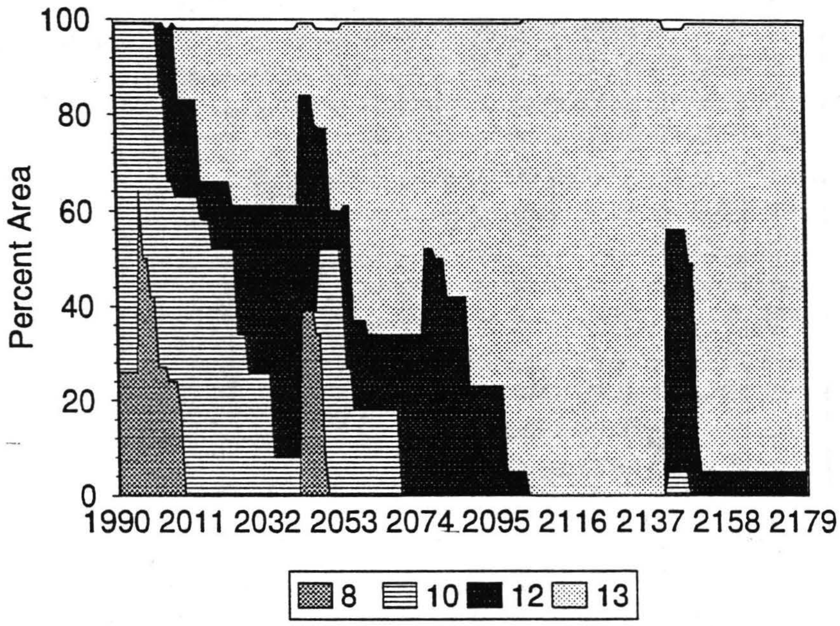


Figure 5.5: Percent of the landscape that would use different static fuel models. Only four fuel models are shown because these are the only ones possible in a forested landscape in which no management occurred.

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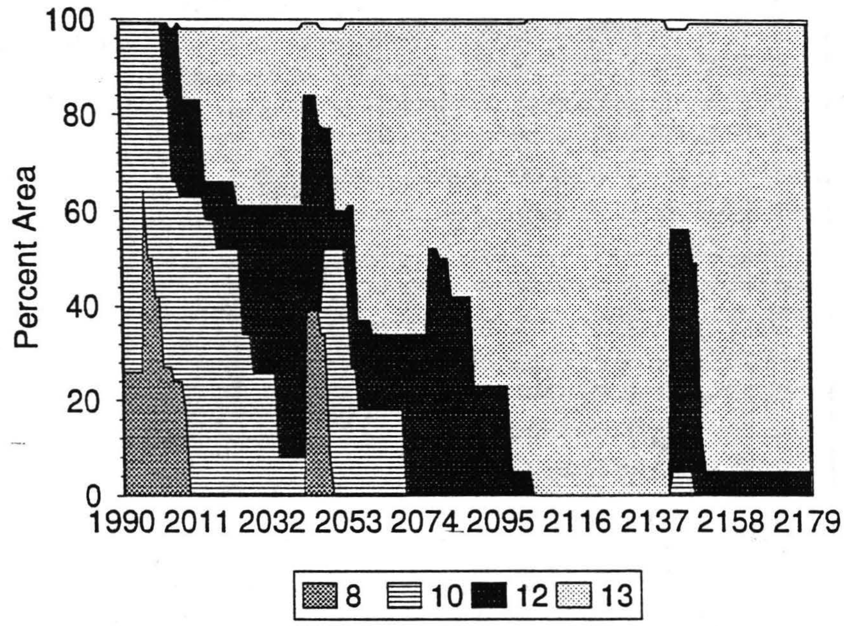

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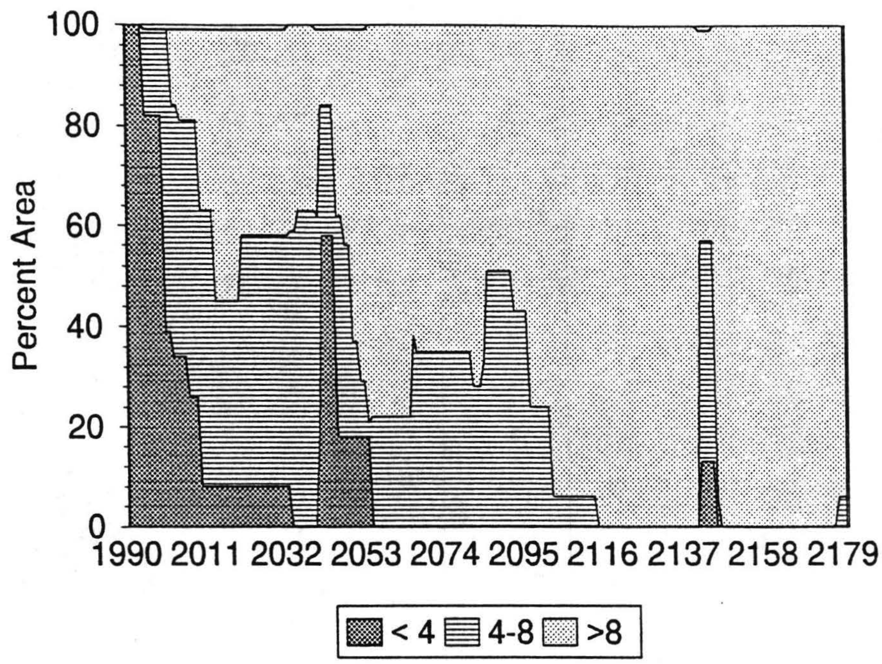
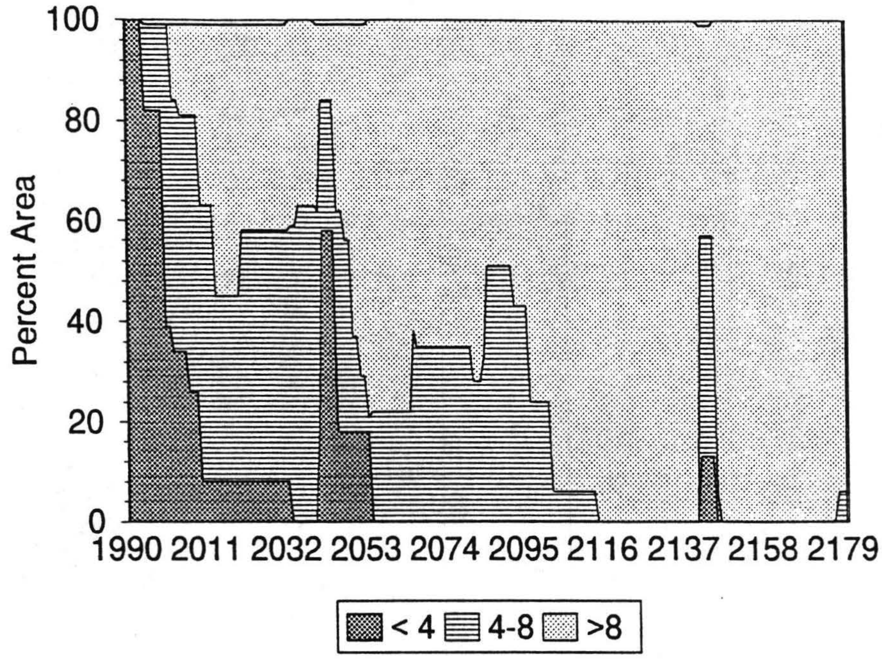


Figure 5.6: Percent of the landscape that would have different flame lengths if a fire occurred under the predefined "very dry" moisture conditions. The area is grouped into the three categories based on the predicted flame length, in feet.

5.5 Scenario Results: Static Fuel Models

The fire model uses a "dynamic" representation of the information contained in the static fuel models to smooth the transition between parameter values as fuel pool change size. This is the option that will operate by default in the model. Users still, however, have the option of changing this method of calculation to using the original static fuel models to choose the parameter values. The runs shown in the previous sections (fires in 2040 and 2140 in five stands and a fire in 1995 in a different four stands) were repeated using the static fuel model instead of the dynamic representation. Little difference occurred in the flame lengths between the two runs (Figure 5.7), and as a consequence, little difference is seen in the stand behavior.



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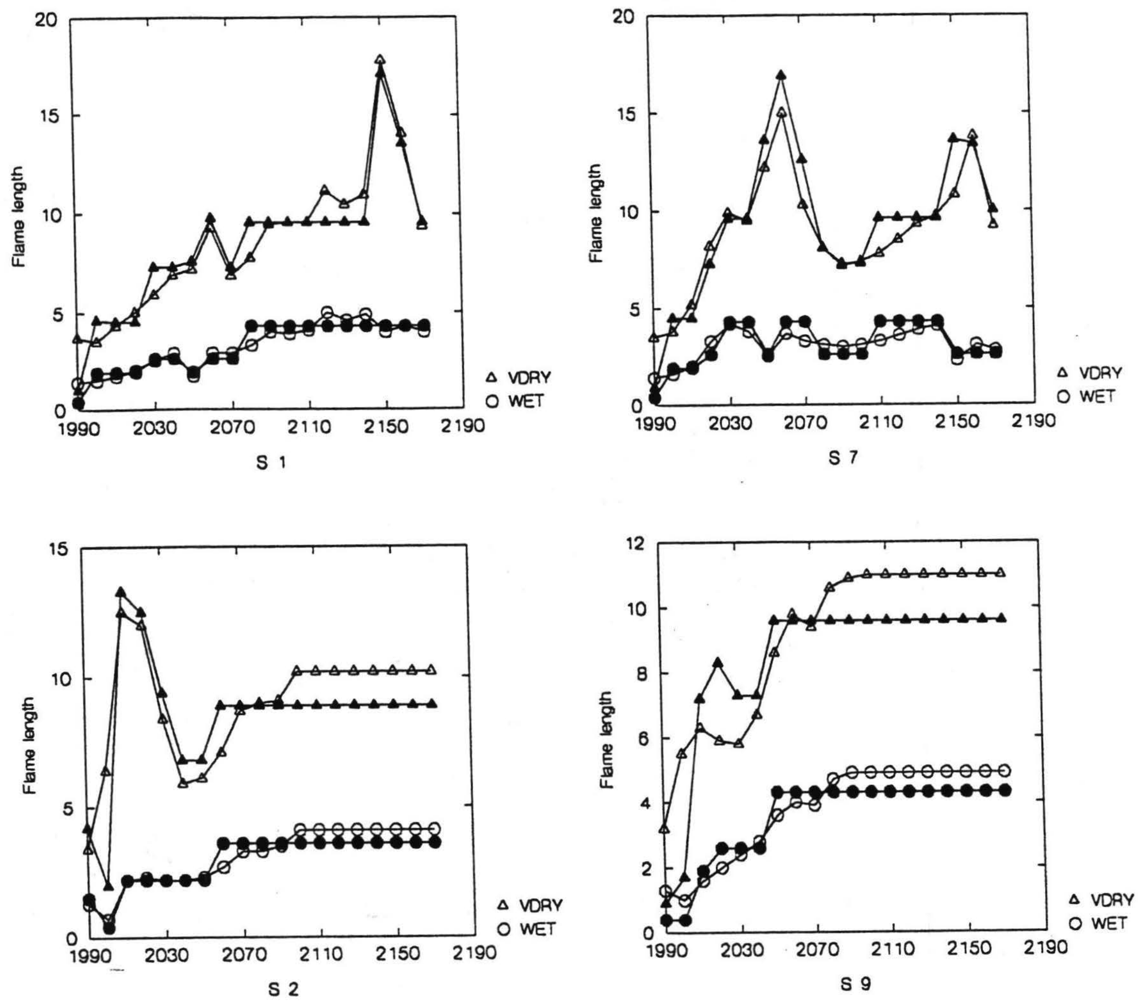
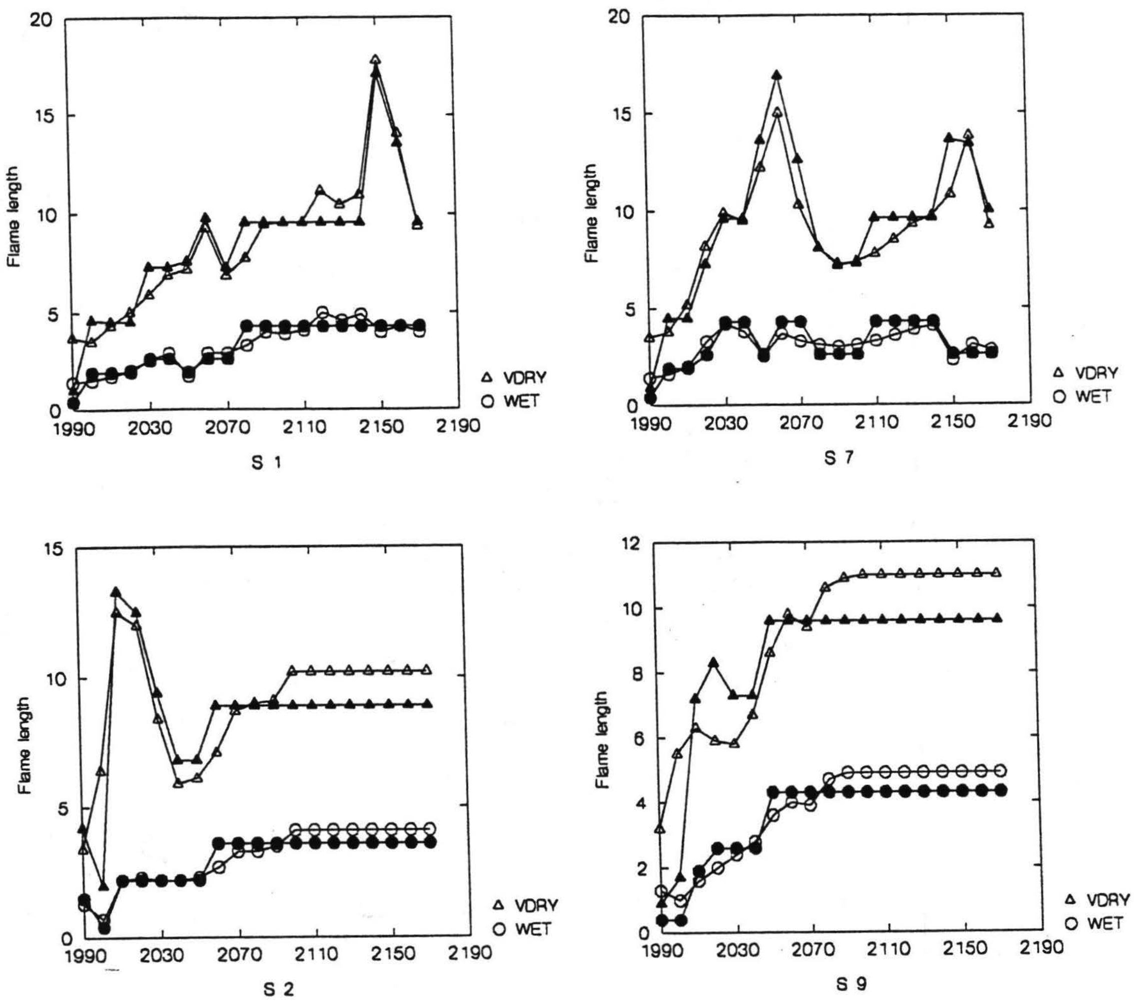


Figure 5.7: Comparison of the flame lengths generated using the "dynamic" or static models. The flame-lengths for the "wet" and the "very dry" conditions are shown for four example stands. Solid symbols are the static fuel model and open symbols are the "dynamic" fuel model. The first two stands have fires in 2040 and 2140 and the last two stands have a fire in 1995.

5.6 Scenario Results: Frequent Fires in Wet Conditions

Stands in some habitat types experience frequent underburns. Fuel dynamics in these stands are quite different than in stands with occasional stand-replacing fires. The landscape was simulated with a series of frequent, less severe fires. Fires occurred every 20 years (starting in 2000), using the pre-defined "wet" conditions. Some stands had the additional assumptions that the fires were "throttle-back", prescribed burns - *i.e.*, the flame-lengths would be lower than those in the stands with basic wild-fires. In all stands, 600 trees/acre of the species listed in Table 5.1 were planted in the stand just after the burn.

Stand and fuel dynamics were quite different in this set of simulations. The difference between the dynamics and effects in the frequent wildfire and frequent prescribed burn runs were very slight, and comparisons were confounded by the fact that, while there are several pairs of stands whose only difference is in the slope (Table 5.1), no two stands are identical. Results from four sample stands are shown in Figure 5.8.



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Stand 1: Wet wildfires

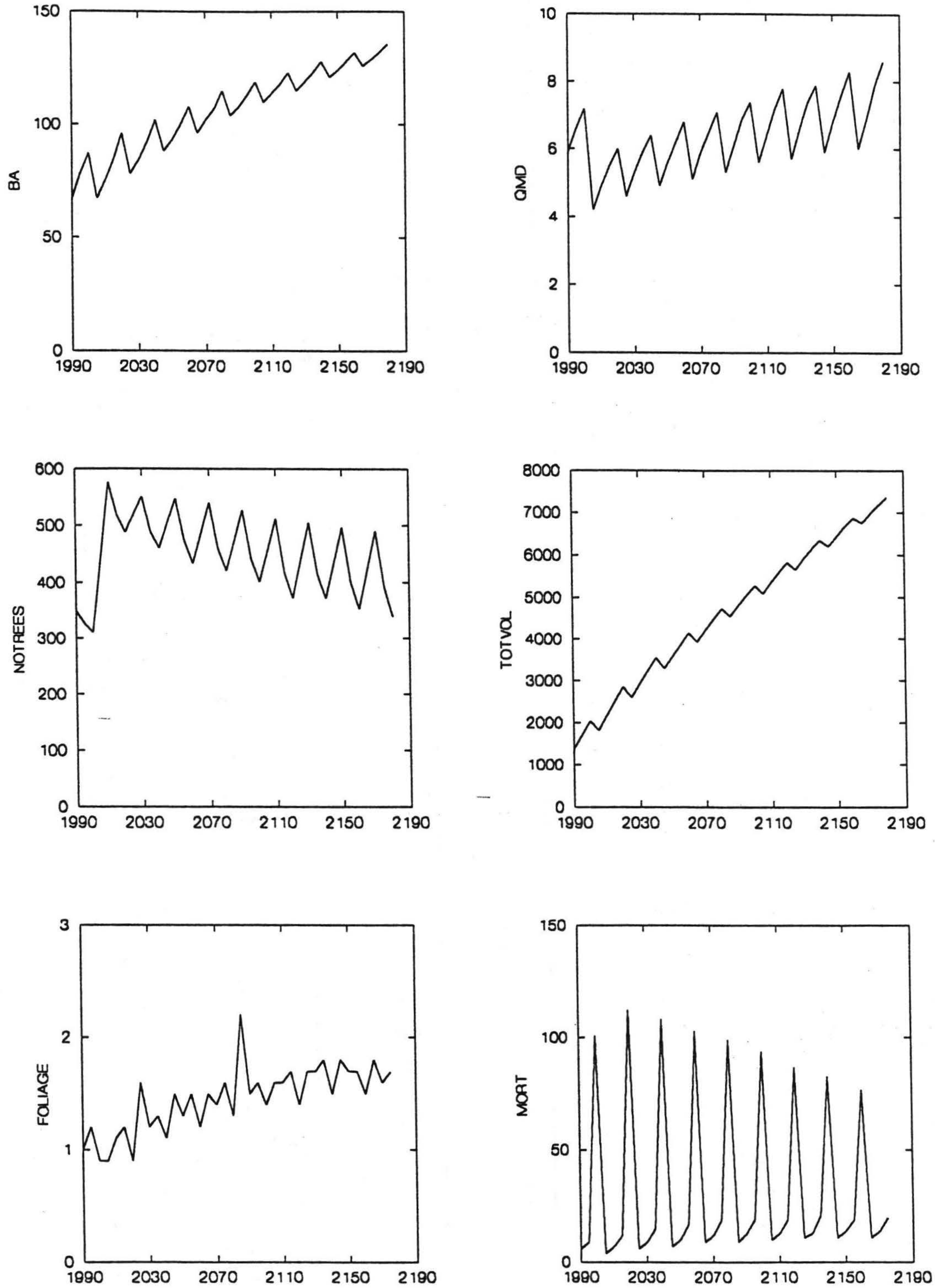

Figure 5.8: Results for some sample stands with frequent, wet burns. Note that the results for each stand are on facing pages. The first two stands show frequent wildfires while the second two stands show frequent prescribed burns. Stands five and six have the same initial conditions except for slope (Table 5.1).

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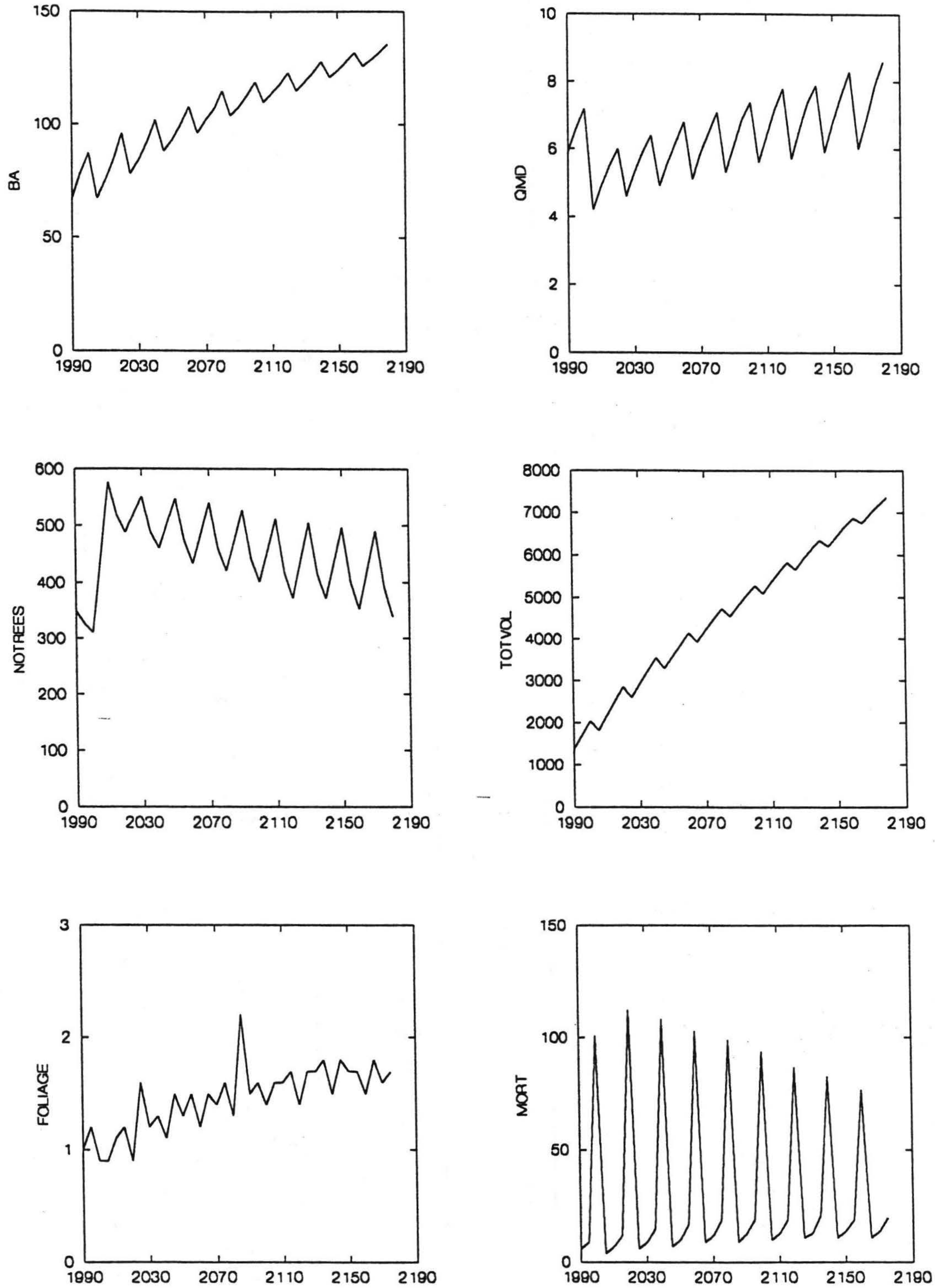

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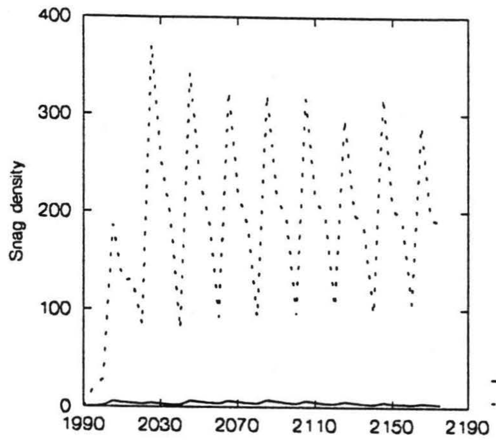

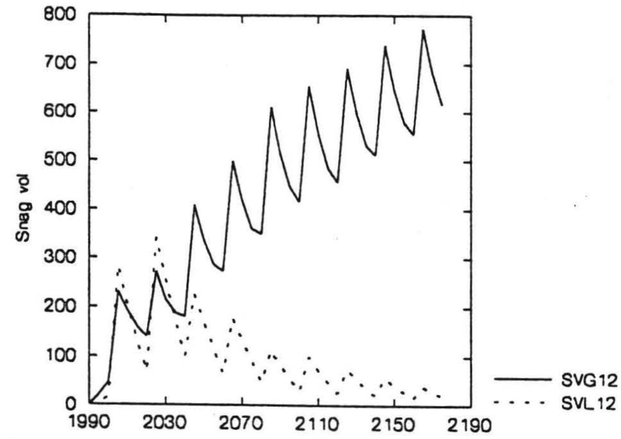

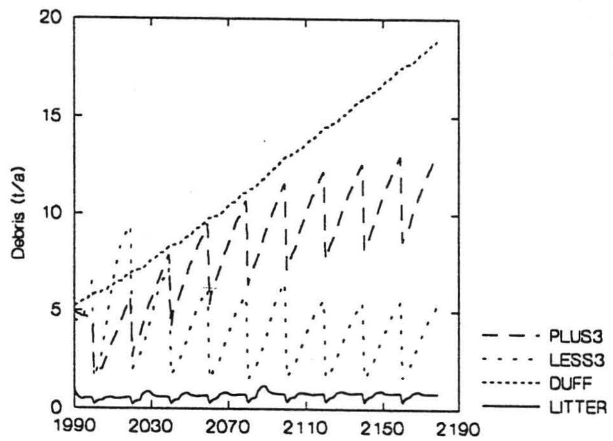

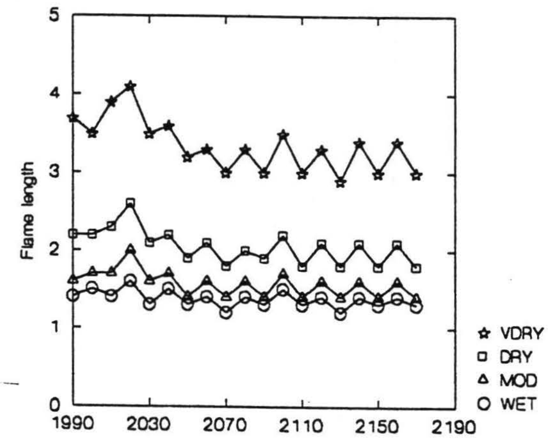

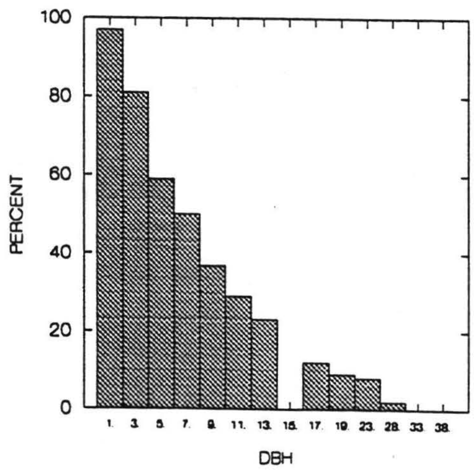

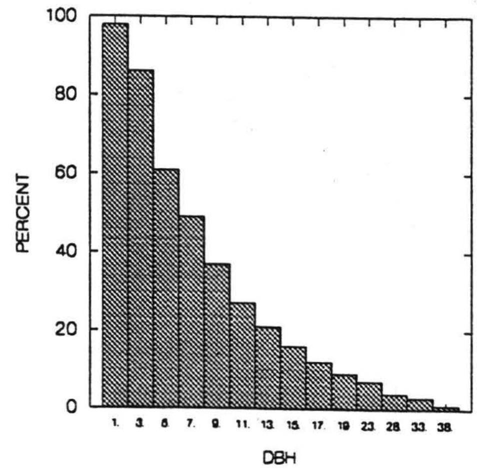

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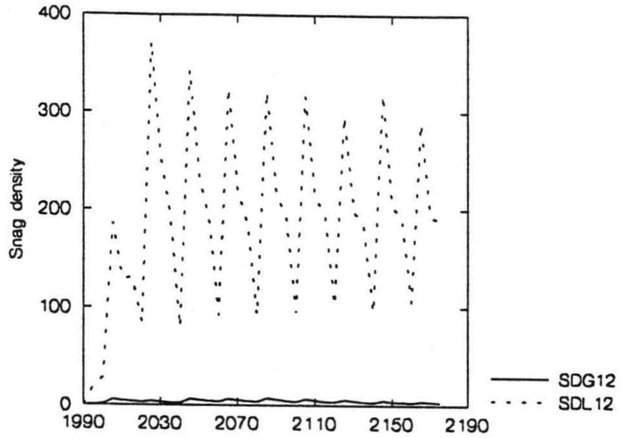
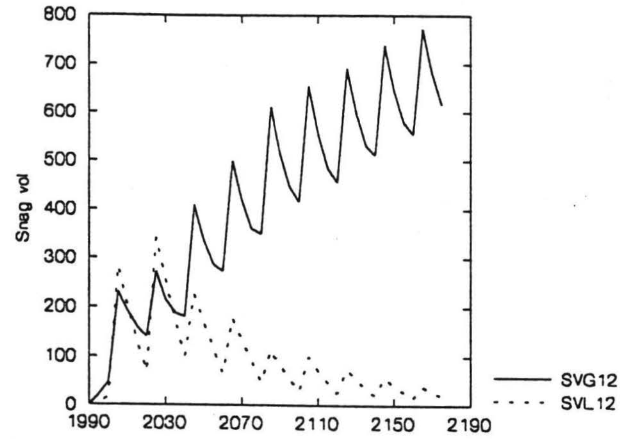
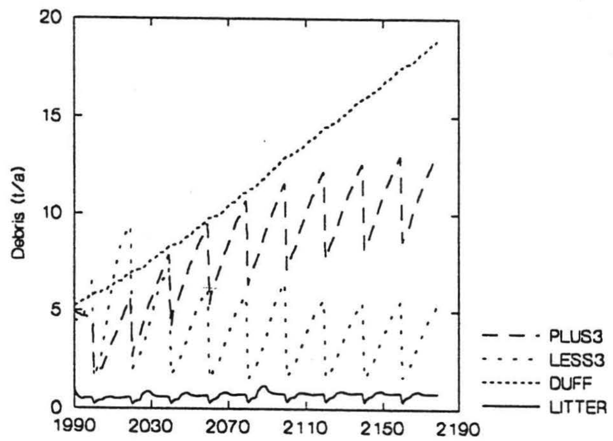
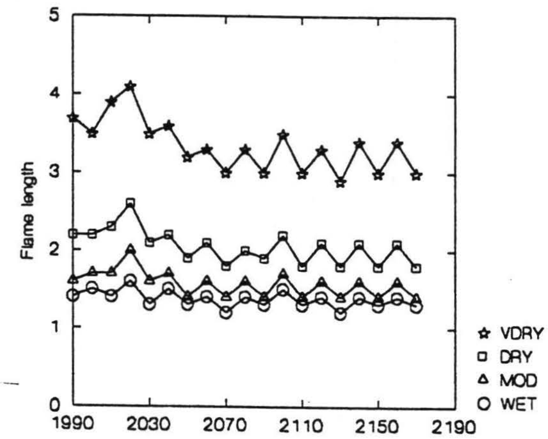
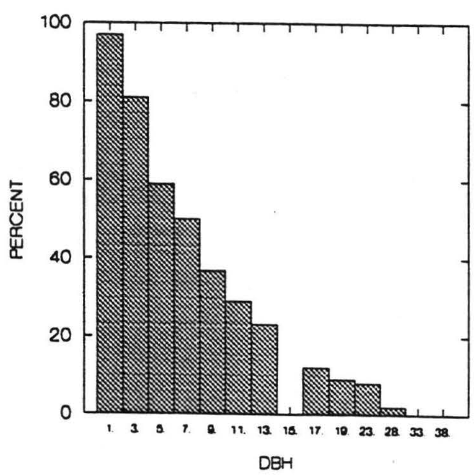
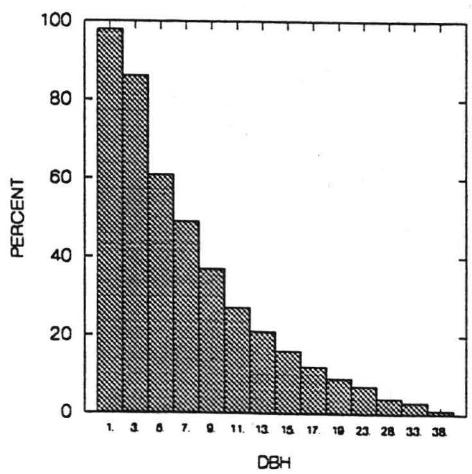




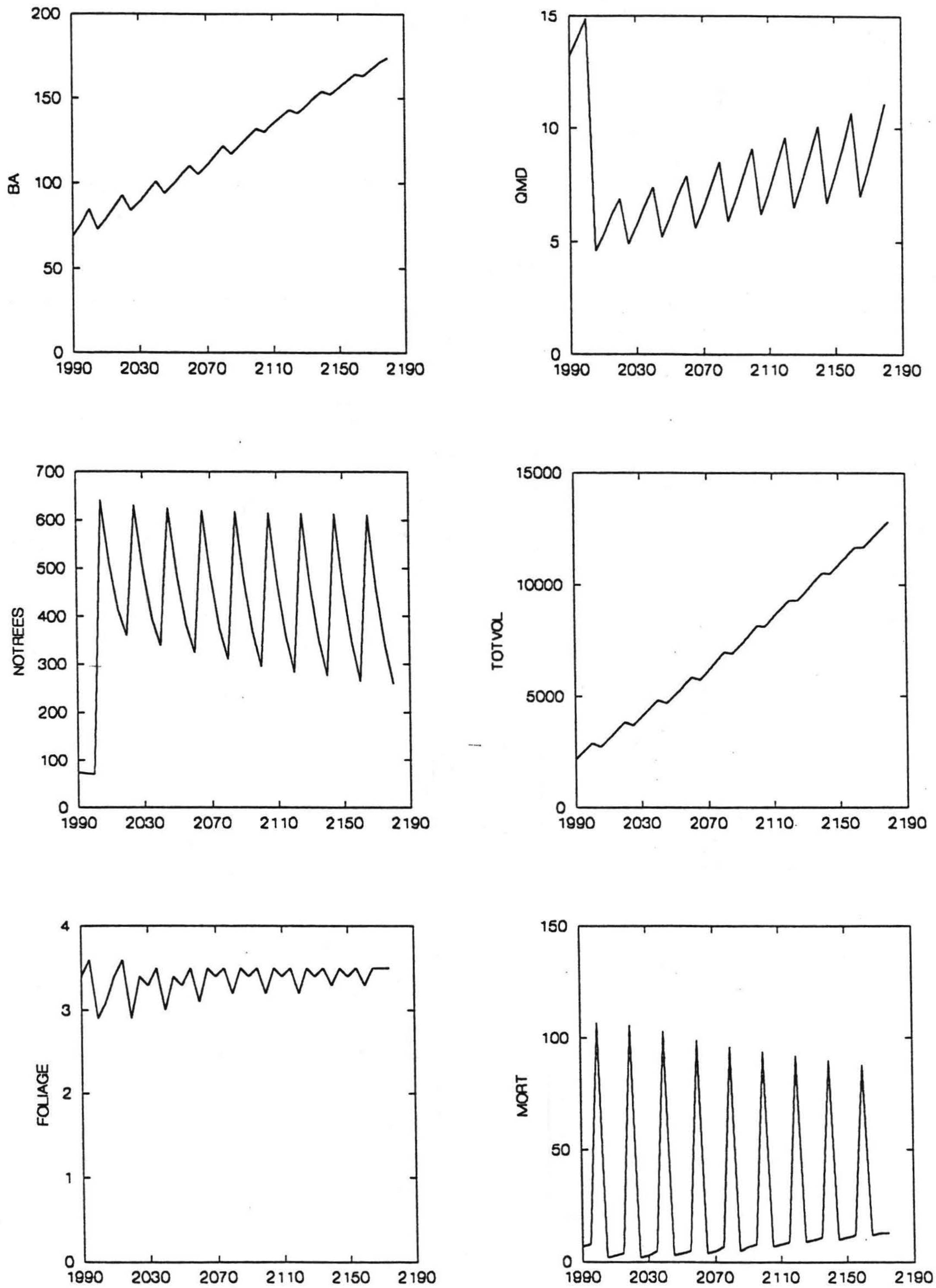




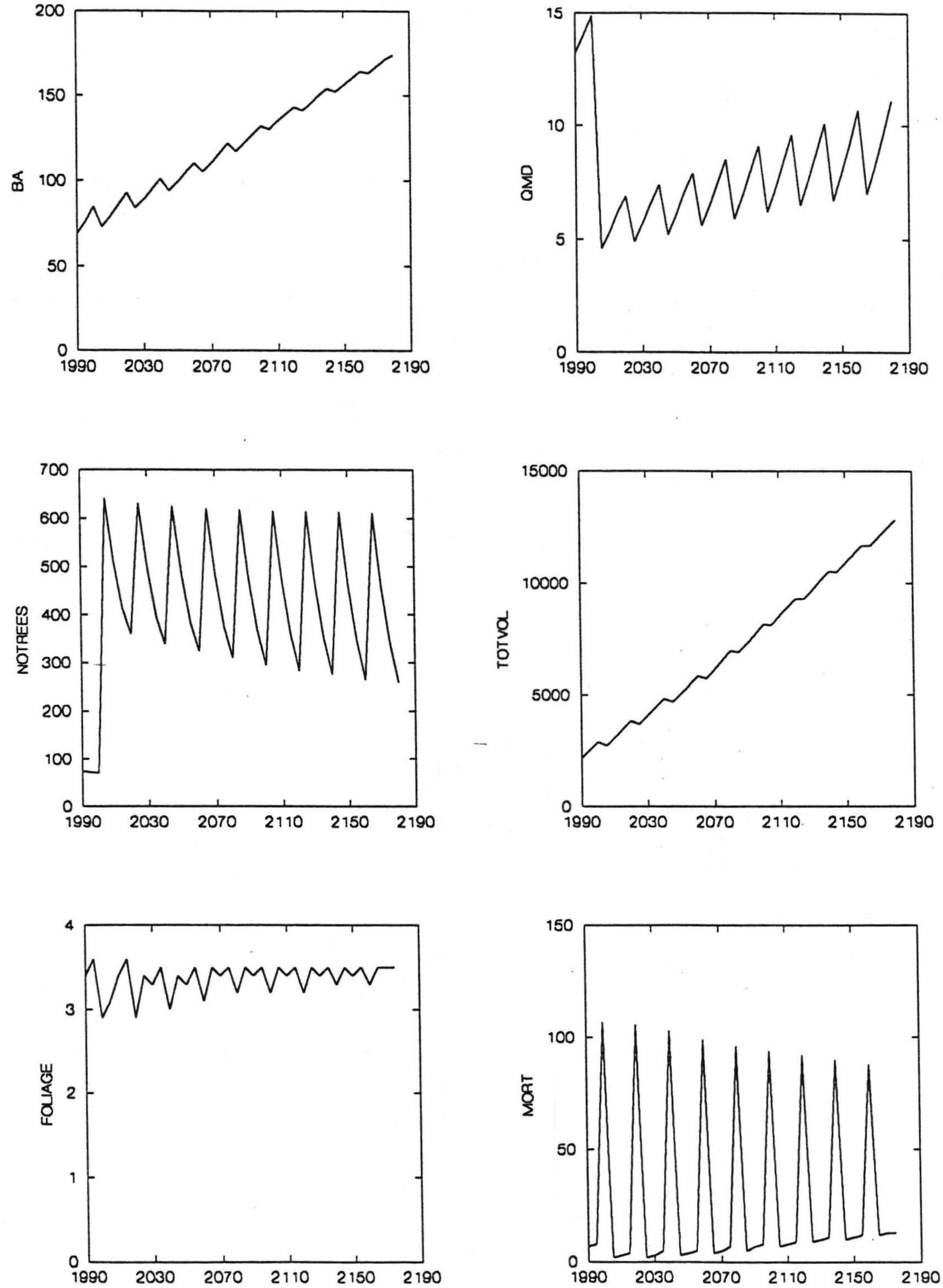




Stand 5: Wet wildfires



Stand 5: Wet wildfires



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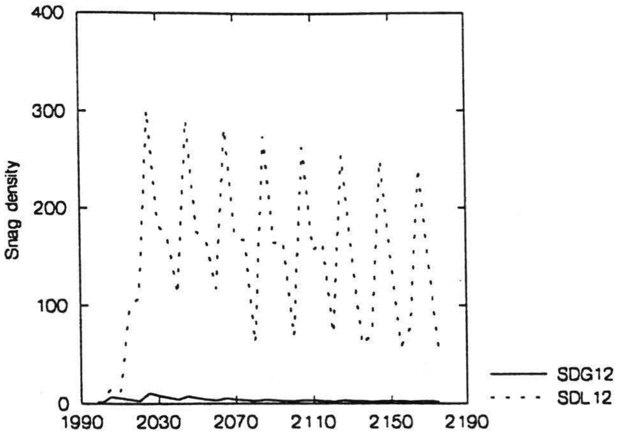

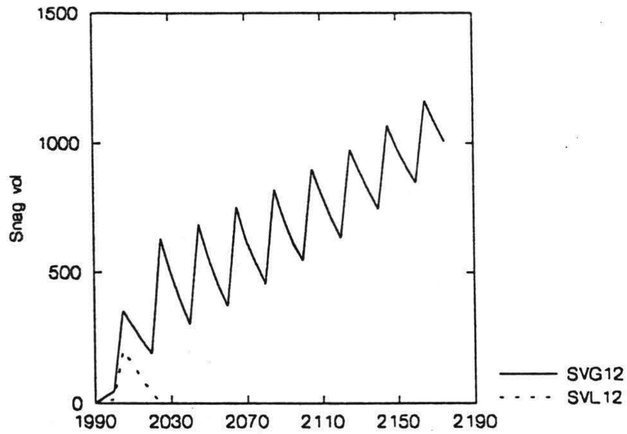

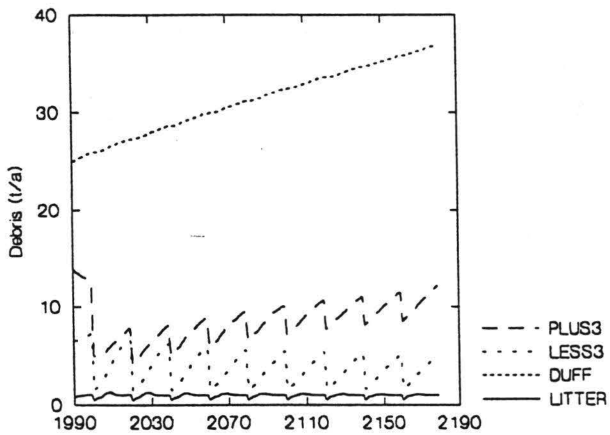

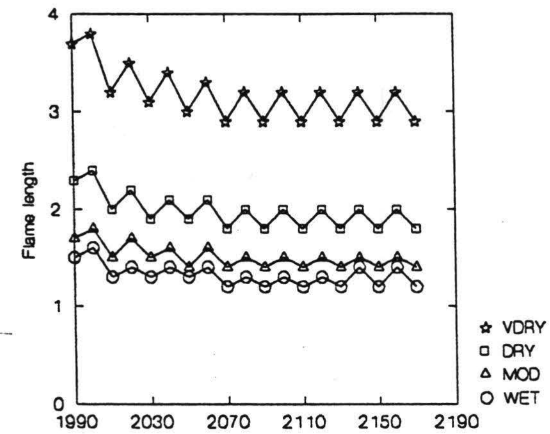

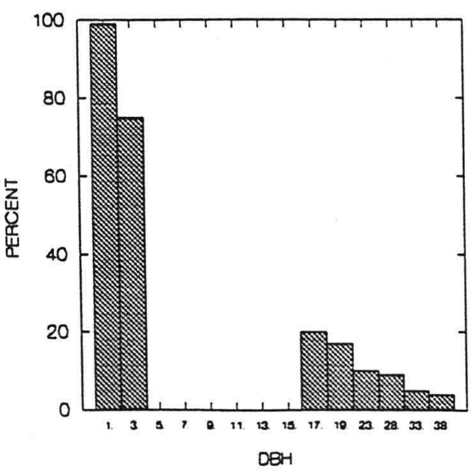

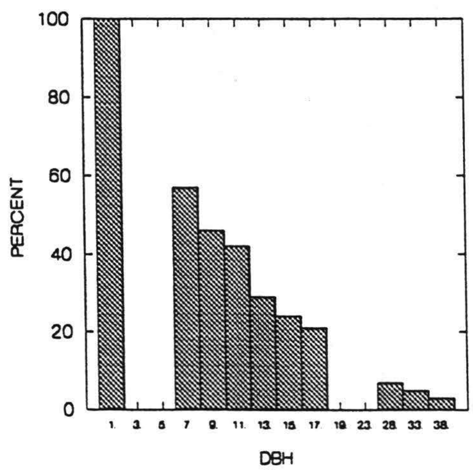

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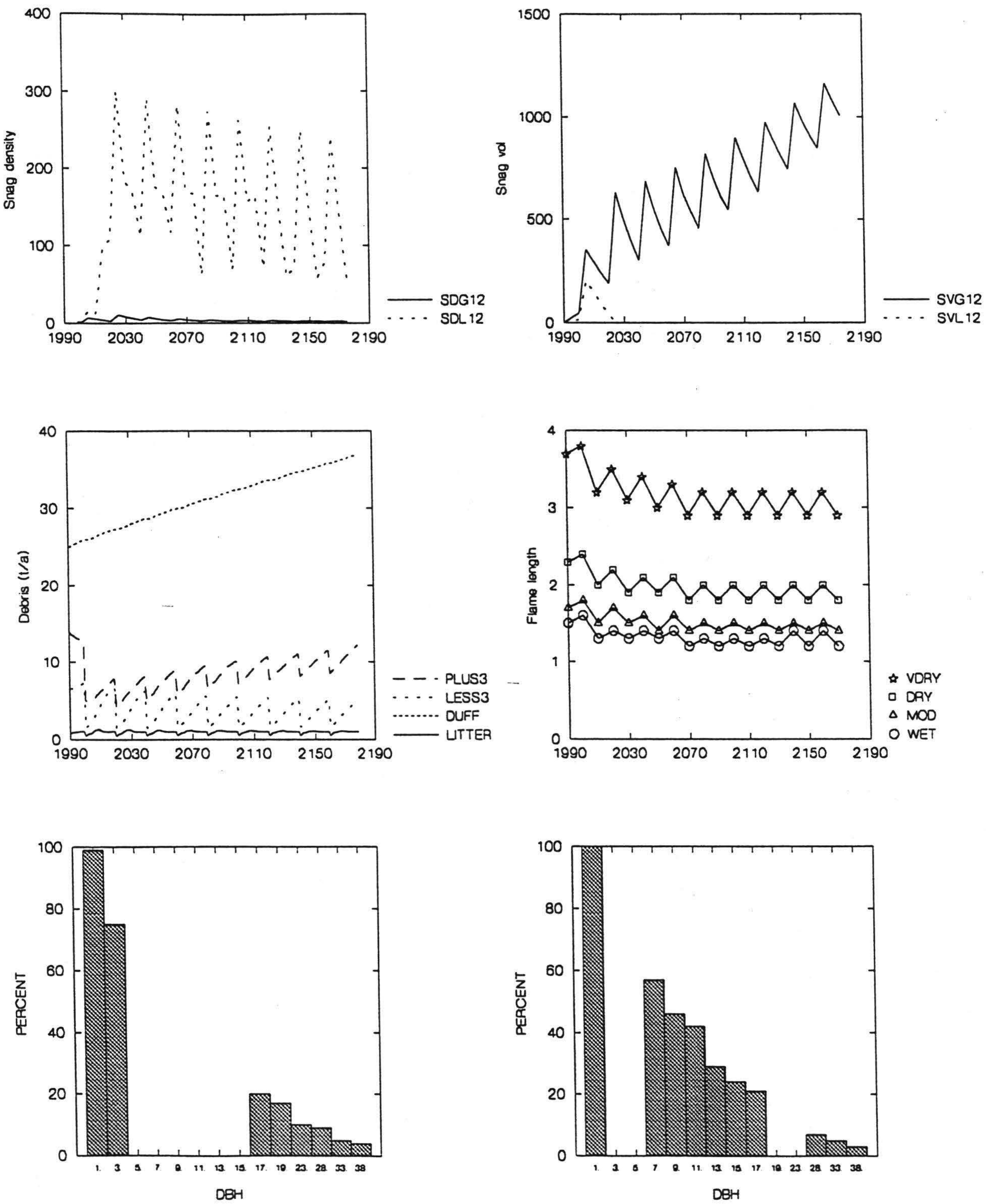
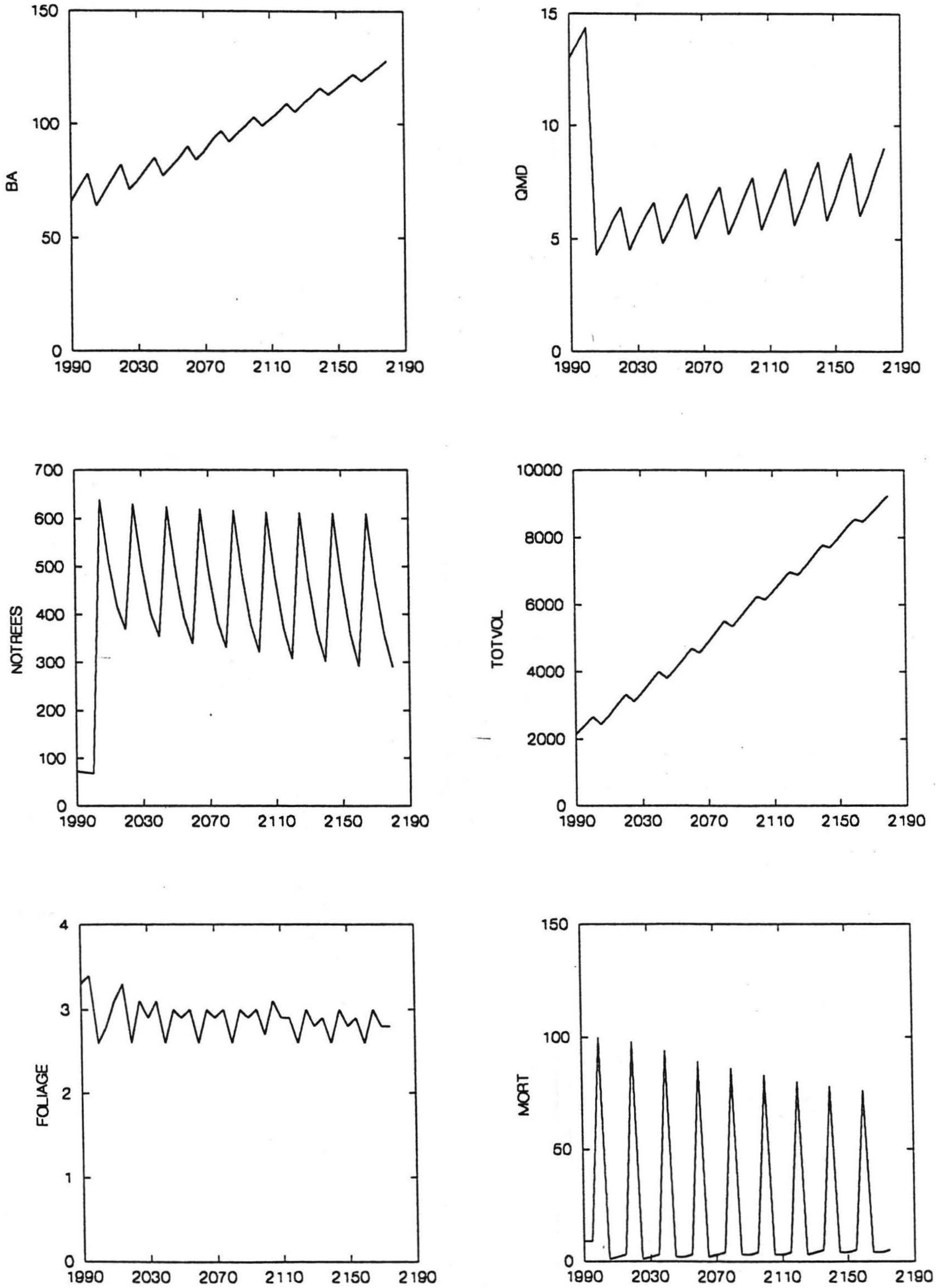


Stand 6: Wet, throttle-back, prescribed burns



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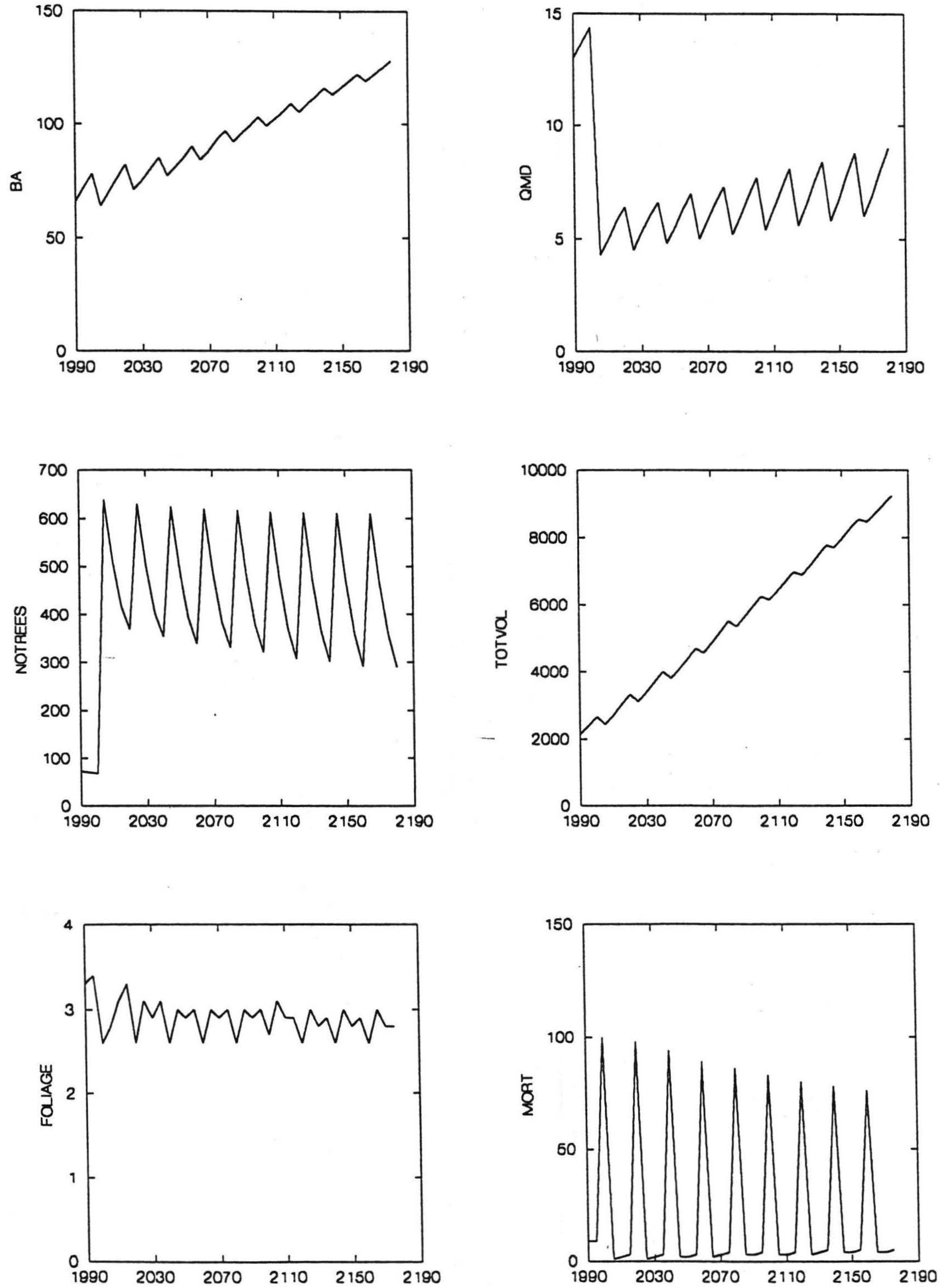

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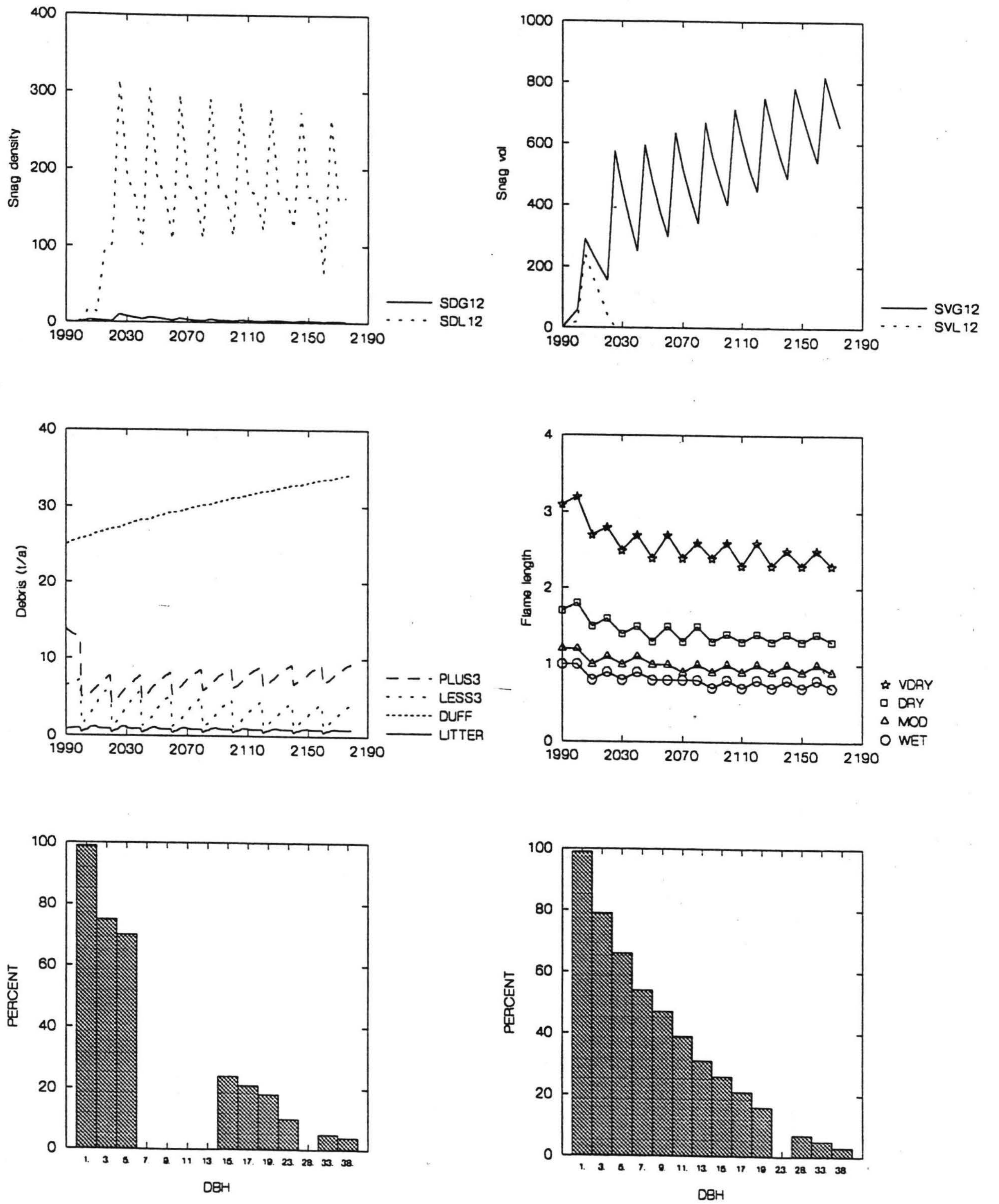

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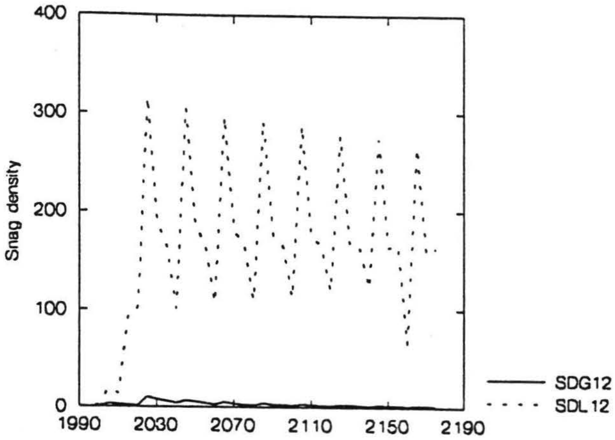
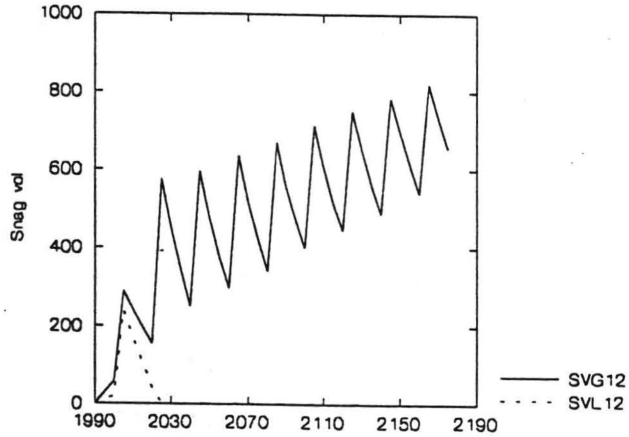
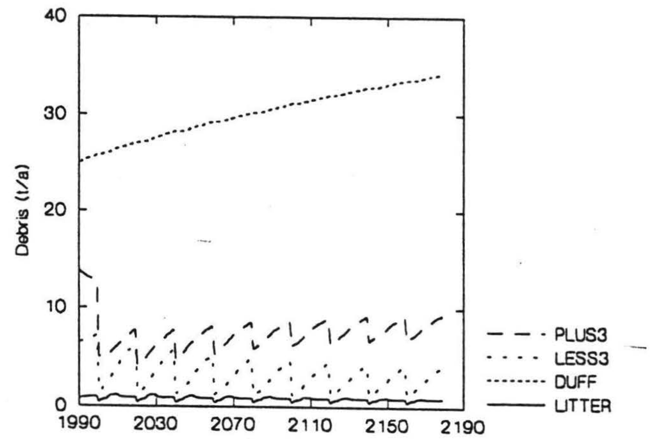
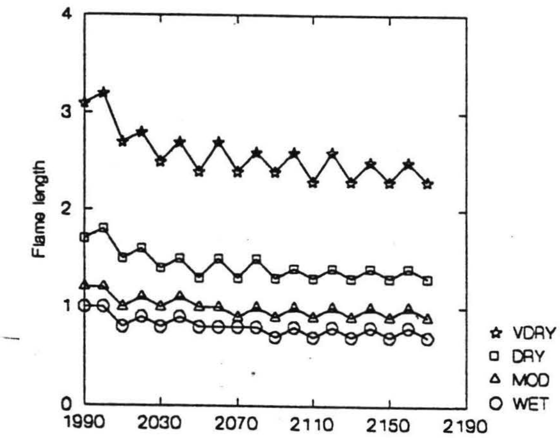
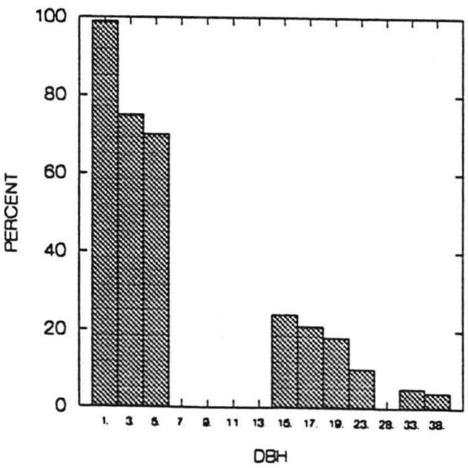
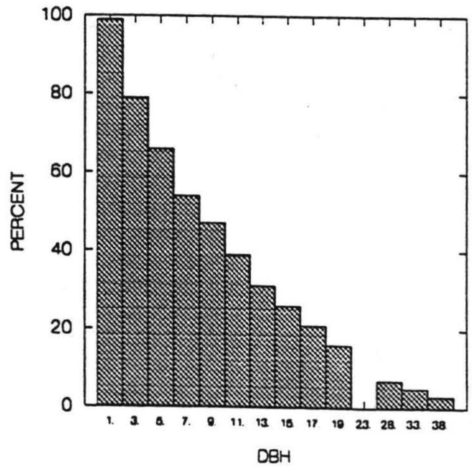




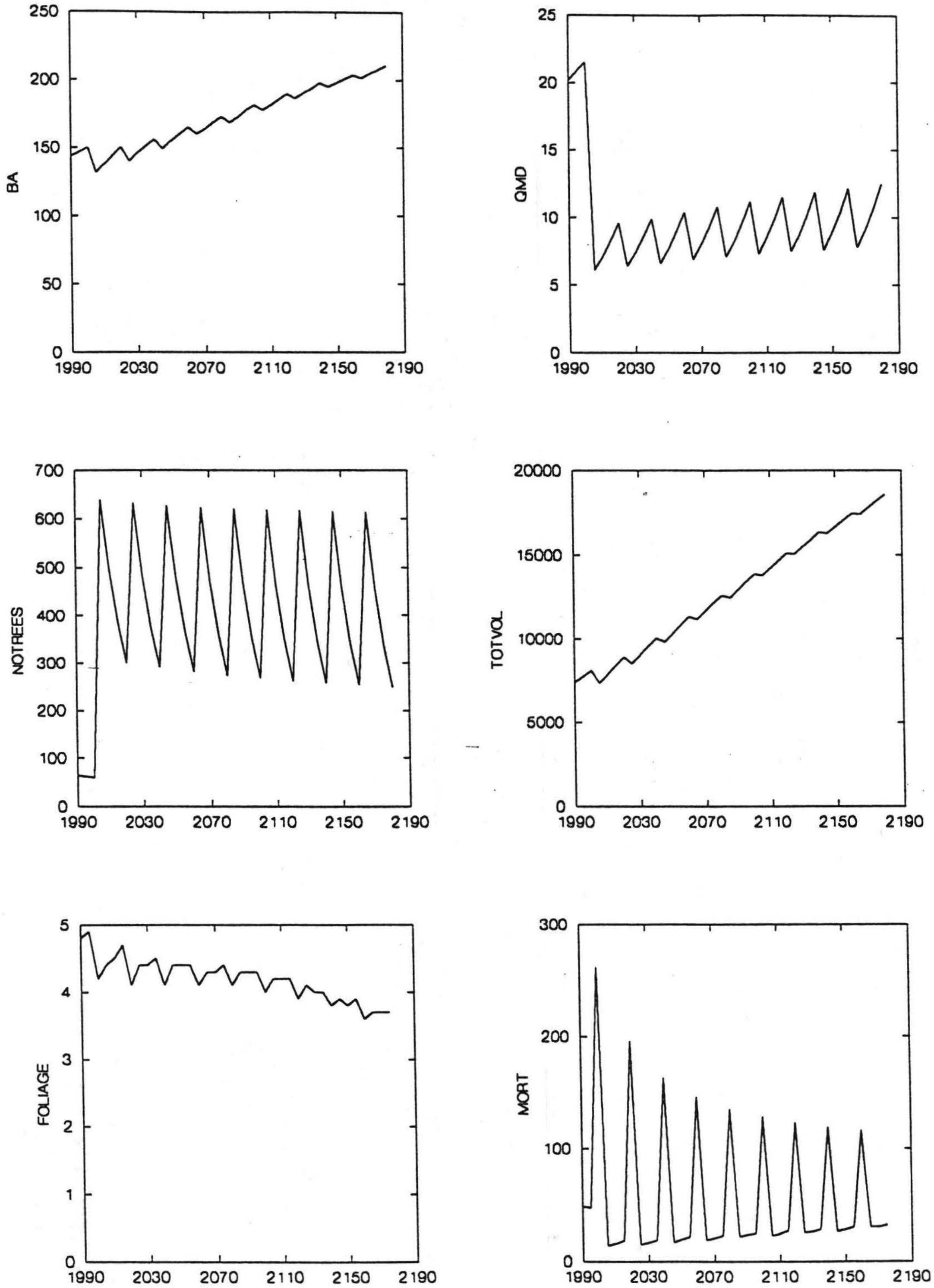








Stand 2: Wet, throttle-back, prescribed burns



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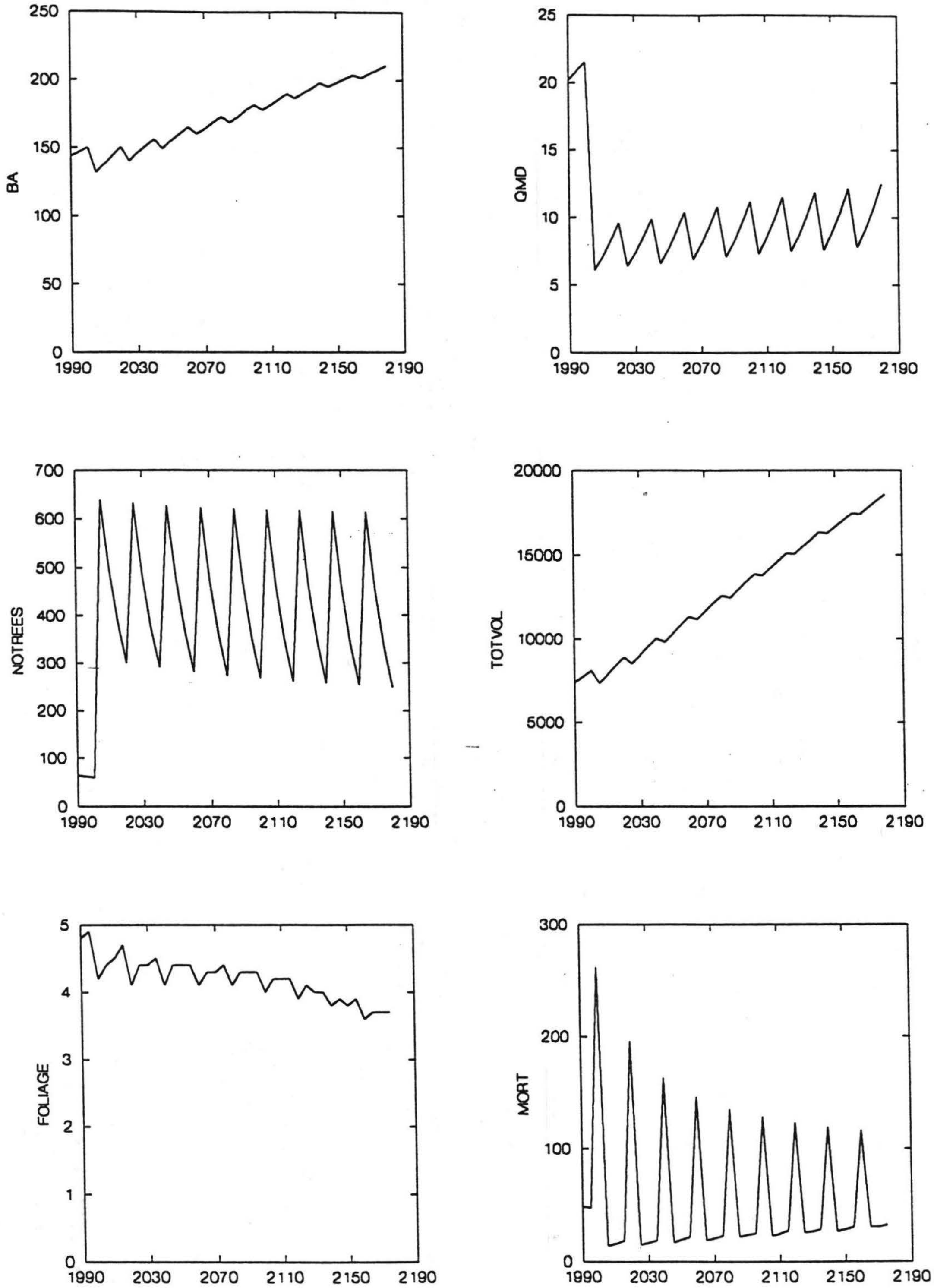

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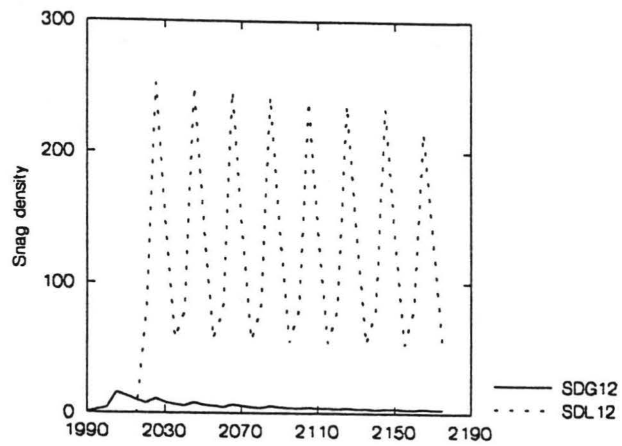

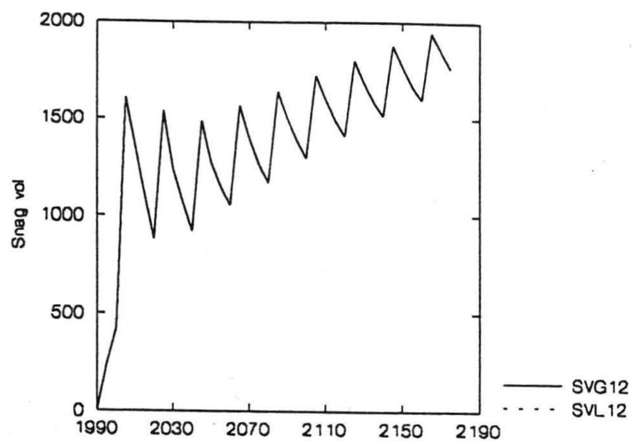

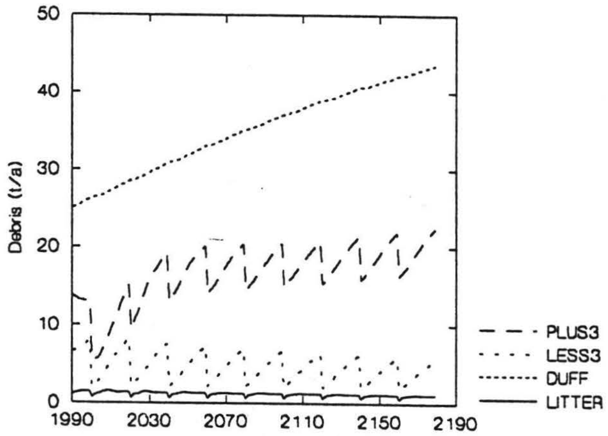

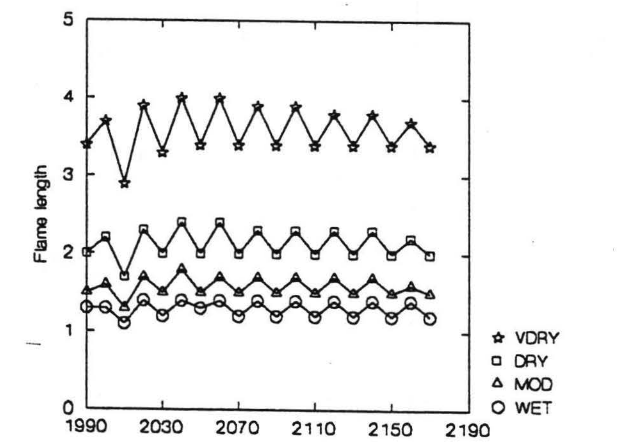

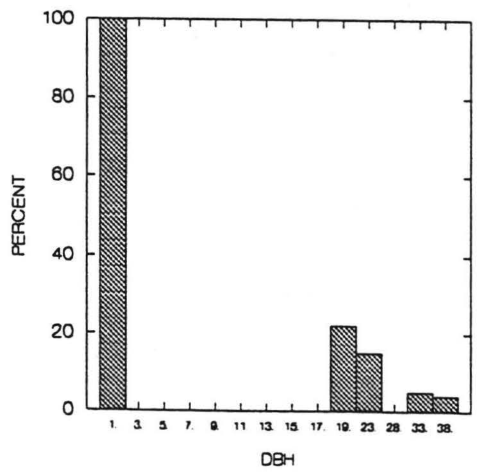

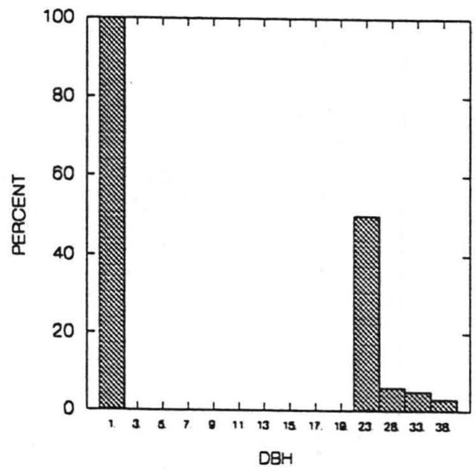

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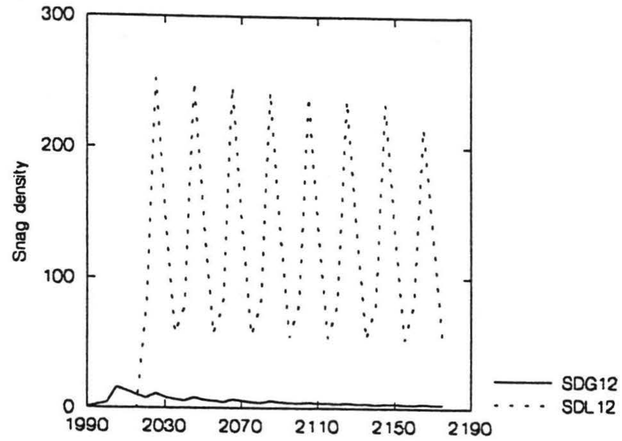

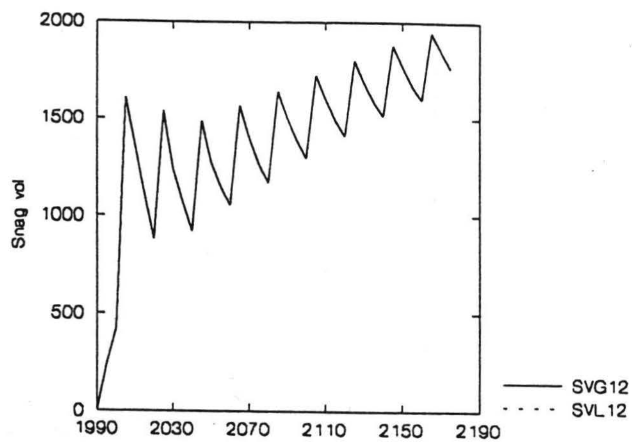

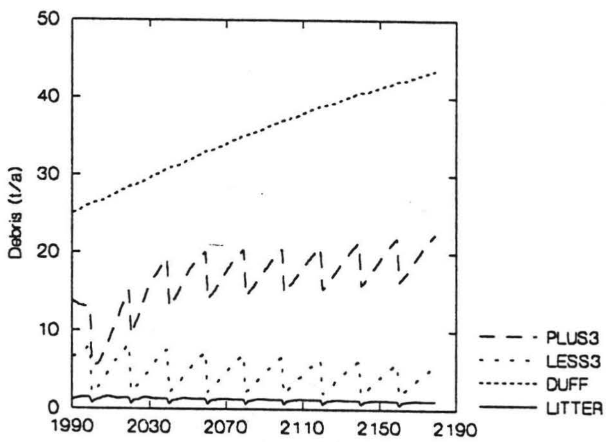

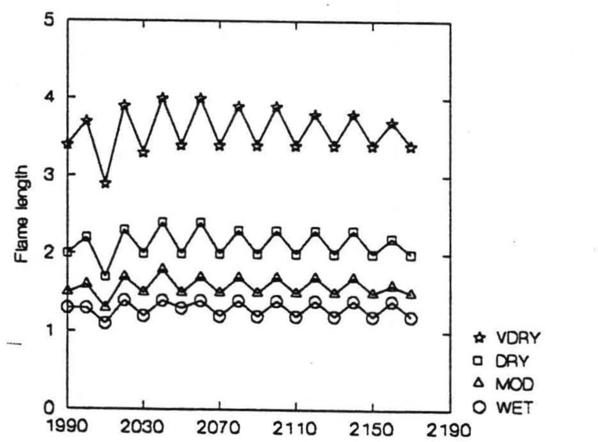

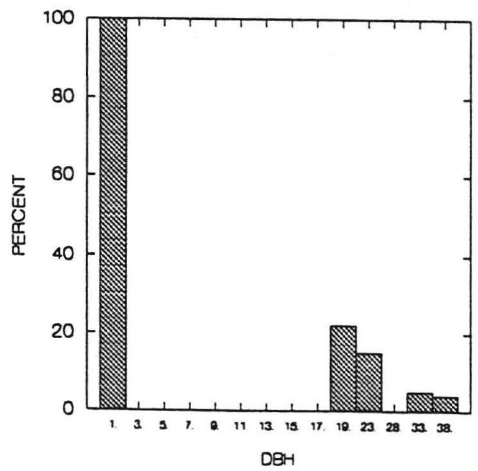

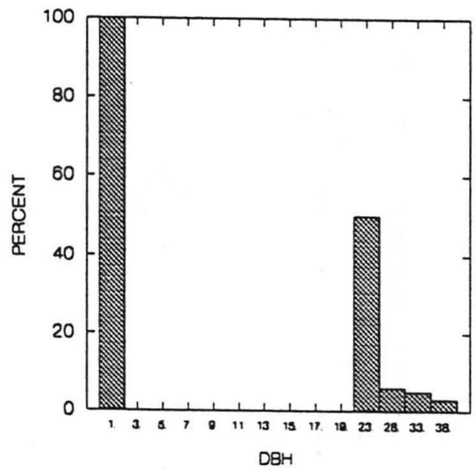

The landscape in this set of simulations can also be characterized according to the percent of the area that would use different static fuel models or that would produce different flame lengths. This landscape is very different from the landscape generated with fewer stand replacing fires. In most years, fuel model 8 would be used throughout 60% of the landscape (Figure 5.9), and even in the other areas or other years, fuel model 13 is rarely used. In all but seven years of the simulation, the predicted flame lengths are less than 8 feet, even in the "very dry" moisture case (Figure 5.10). In most areas in most years, over half the landscape these flame-lengths would be less than 4 feet.

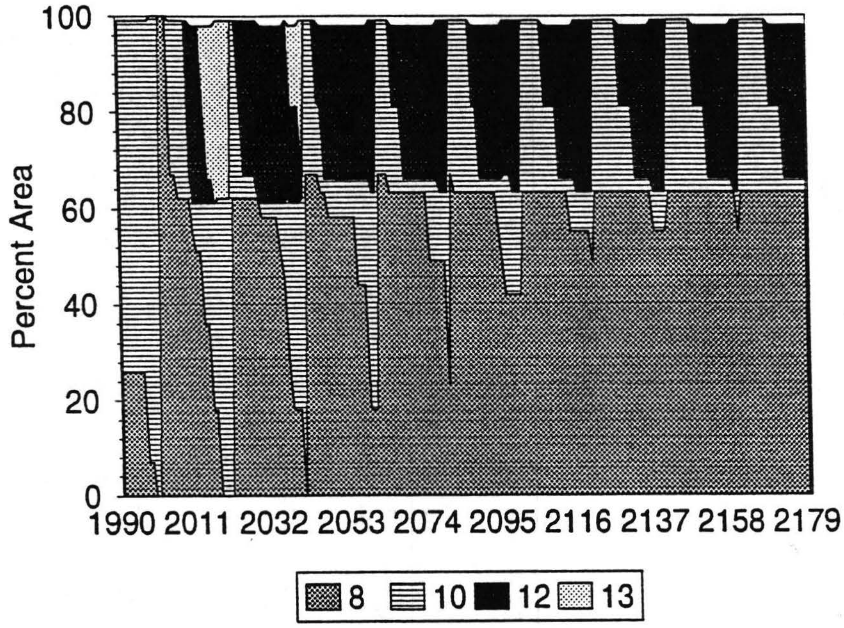

Figure 5.9: Percent of the landscape in each static fuel model. Only four fuel models are shown because these are the only ones possible in a forested landscape in which no management occurred.

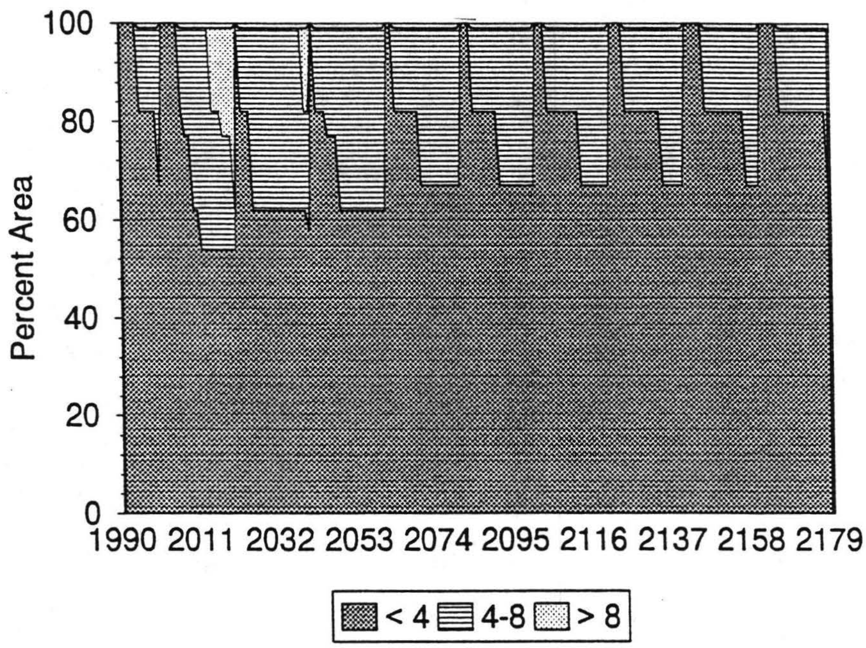

Figure 5.10: Percent of the landscape in each potential flame length group if a fire occurred under the predefined "very dry" moisture conditions. The area is grouped into the three categories based on the predicted flame length, in feet.

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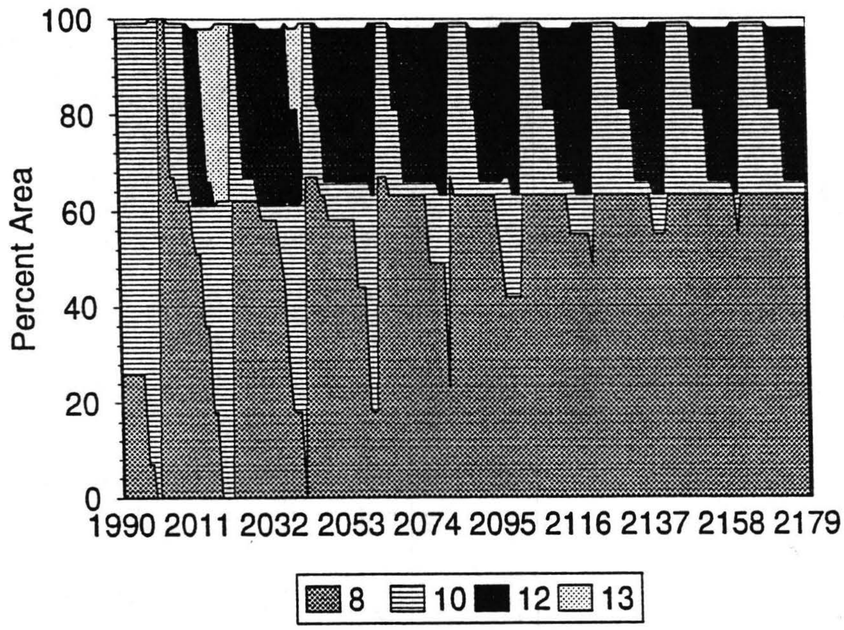

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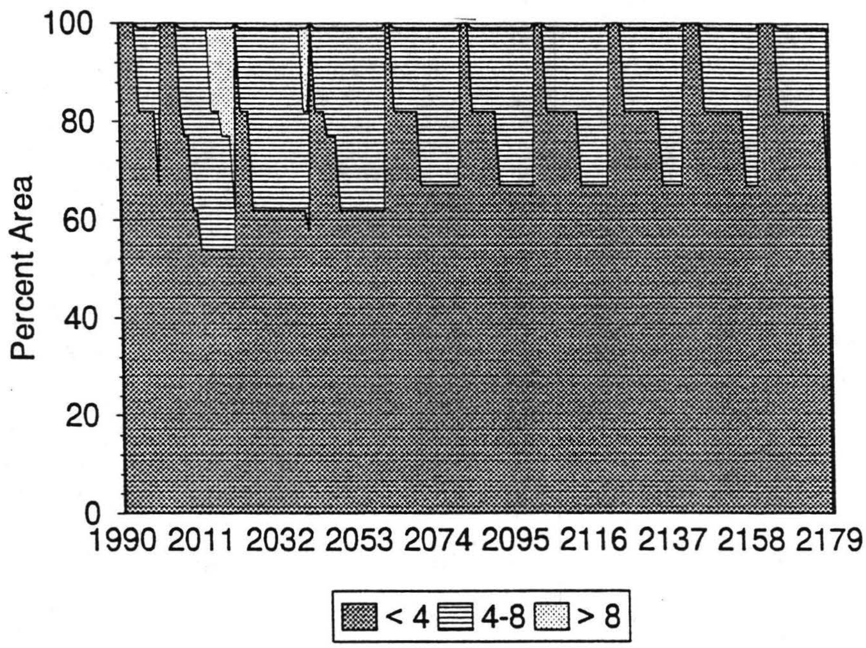

Figure 5.10: Percent of the landscape in each potential flame length group if a fire occurred under the predefined "very dry" moisture conditions. The area is grouped into the three categories based on the predicted flame length, in feet.

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